



Majorana modes in Atomic Chains on the Surface of a Superconductor

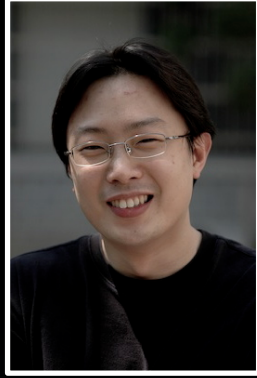
Stevan Nadj-Perge
TU DELFT
CALTECH

Acknowledgments

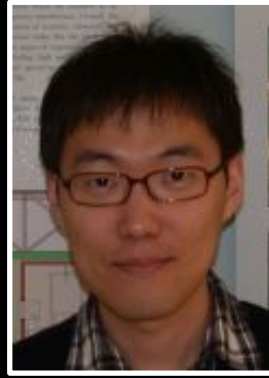
Experiment



Ilya Drozdov



Sangjun Jeon



Jungpil Seo



Prof. Ali Yazdani



Theory



Jian Li



Prof. B. A. Bernevig



Hua Chen

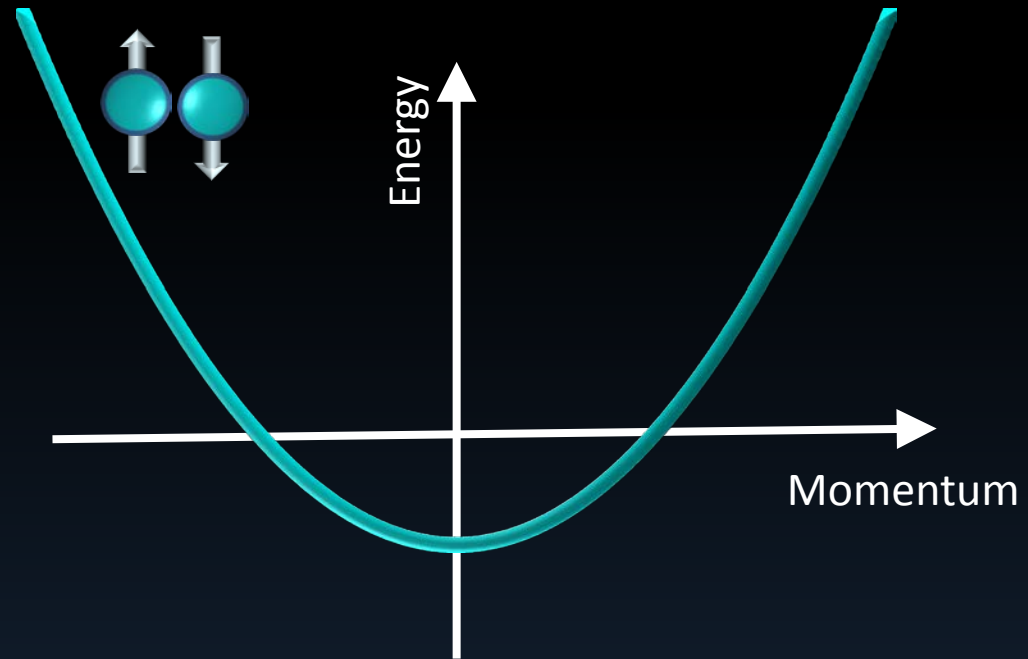


Prof. Allan MacDonald

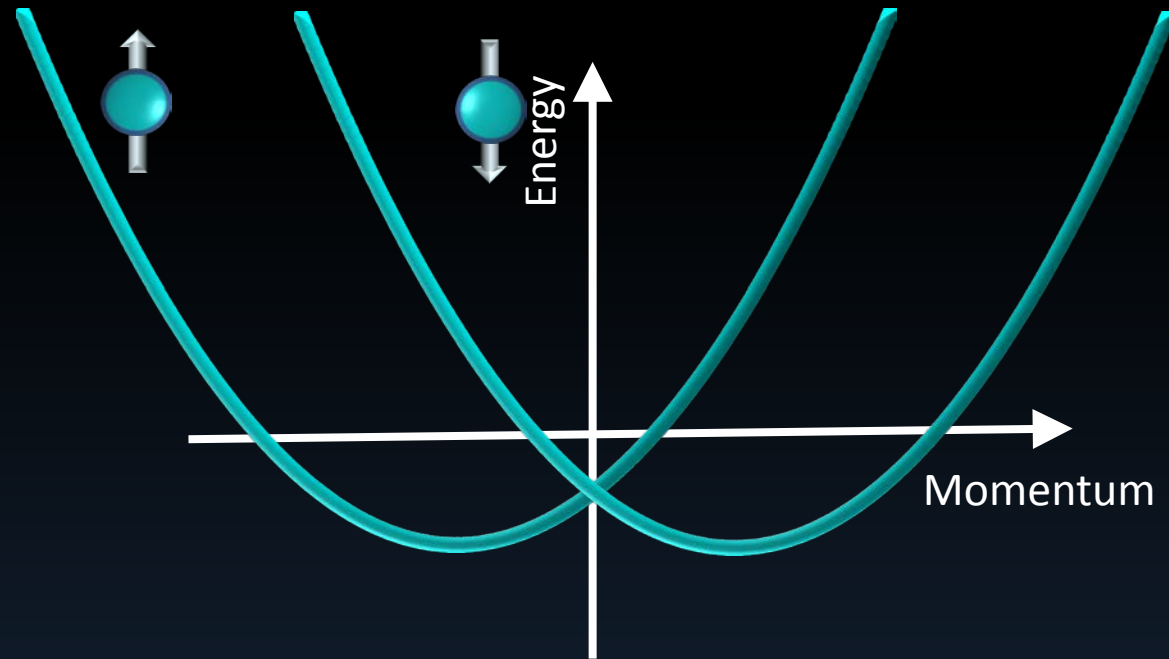
UT Austin



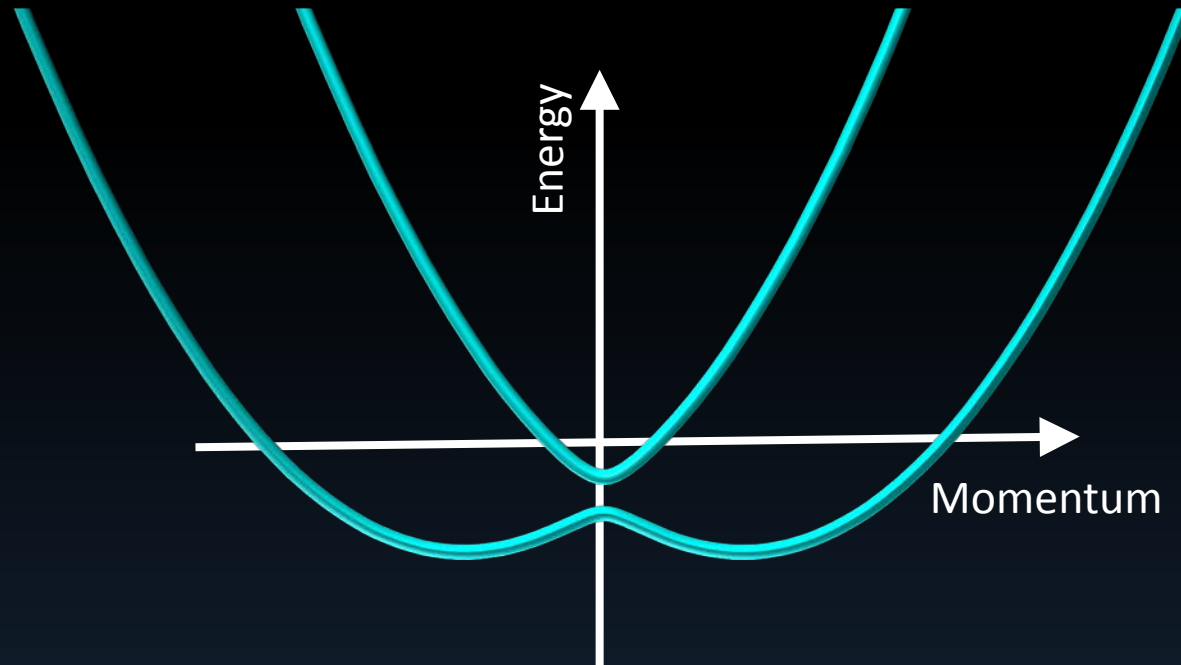
Topology & band structure



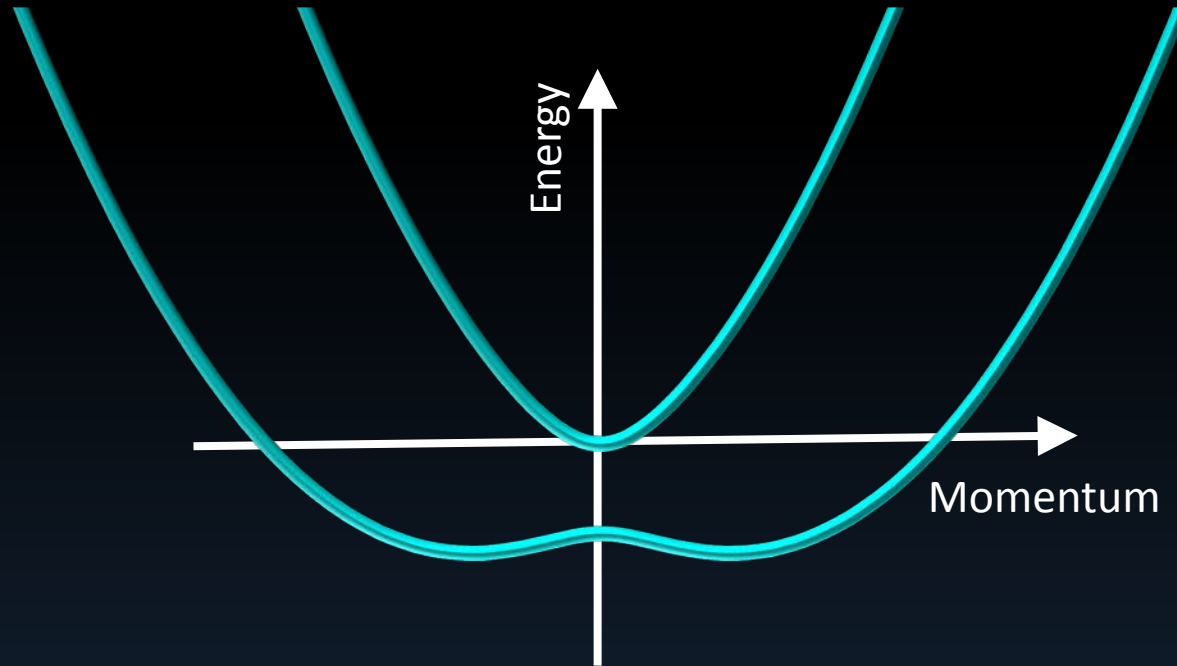
SPIN ORBIT INTERACTION (SOI)



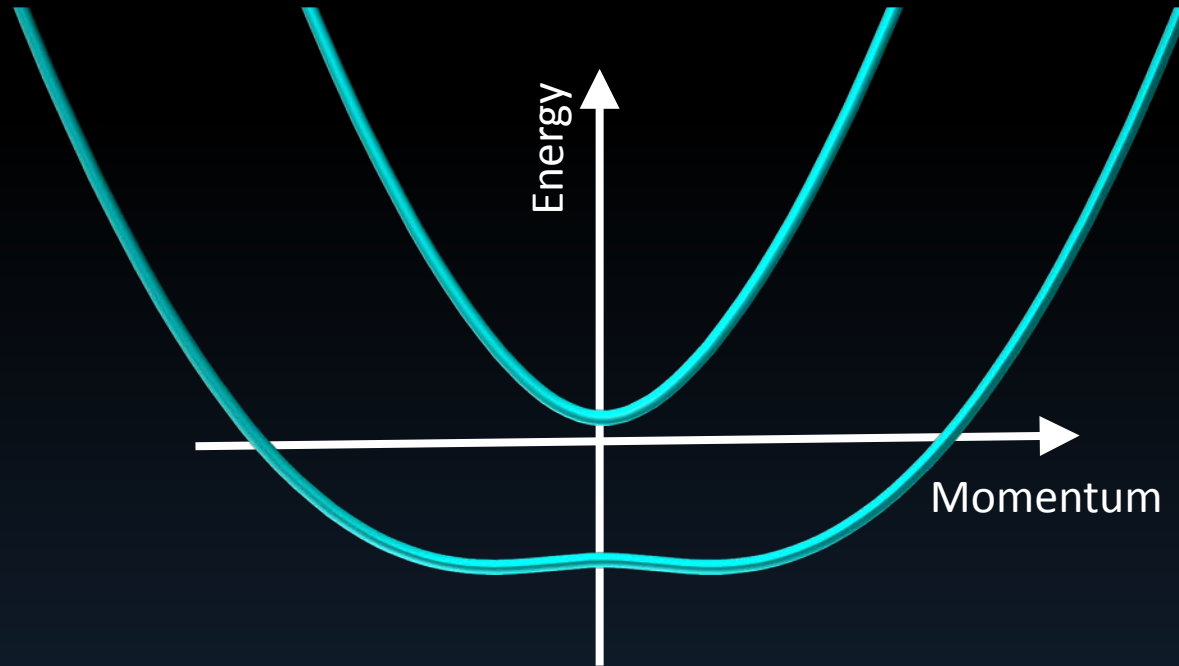
SOI+Magnetism



SOI + Magnetism

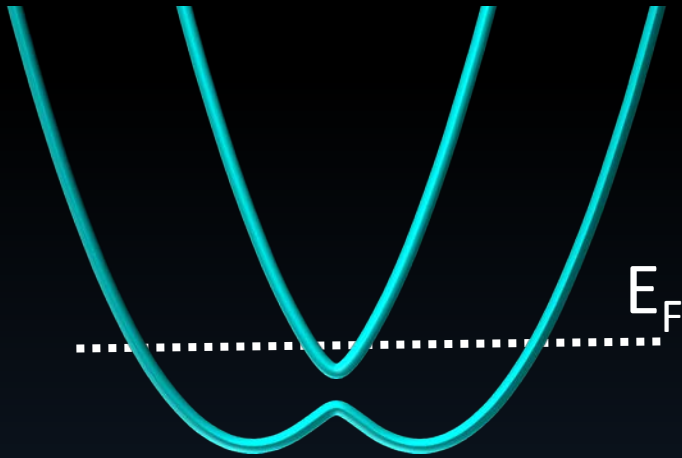


SOI + Magnetism

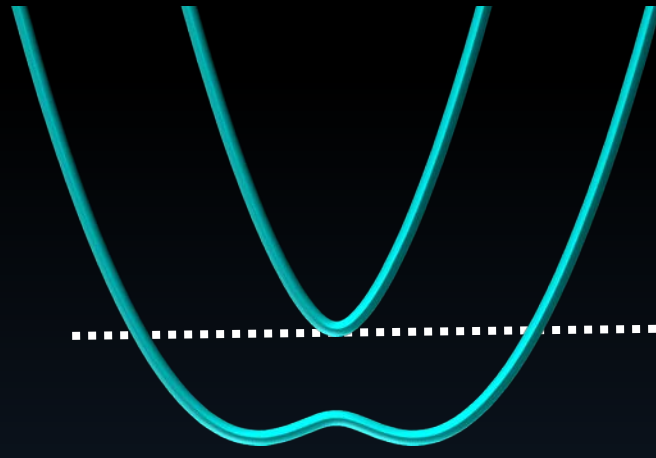


SOI + Magnetism

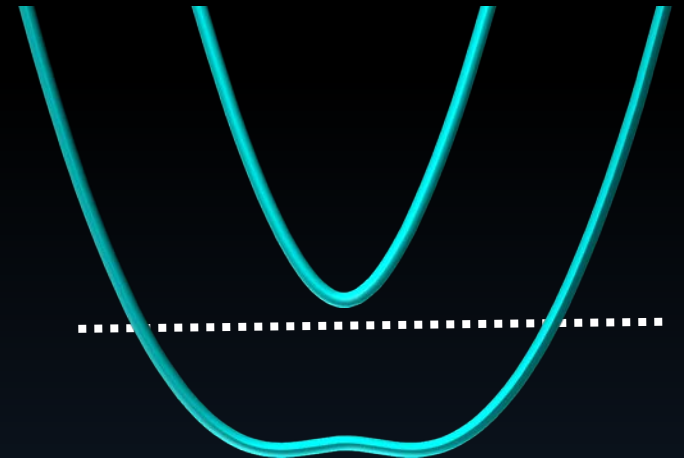
$B < B_{\text{critical}}$



$B = B_{\text{critical}}$

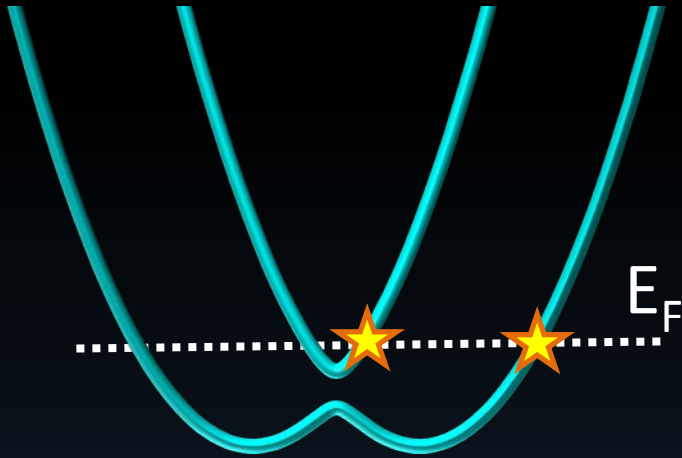


$B > B_{\text{critical}}$

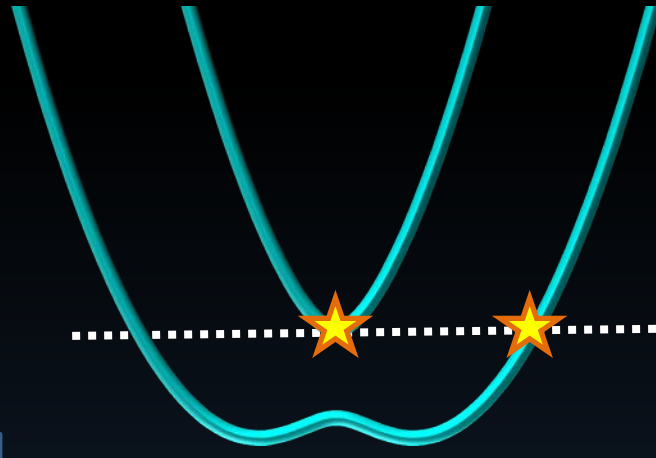


SOI + Magnetism

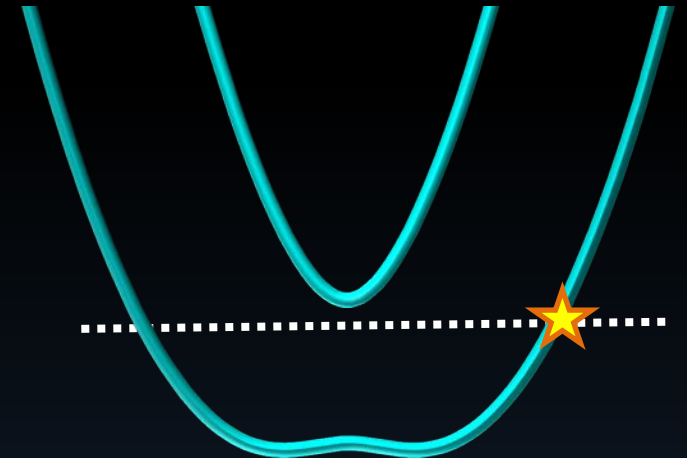
$$B < B_{\text{critical}}$$



$$B = B_{\text{critical}}$$



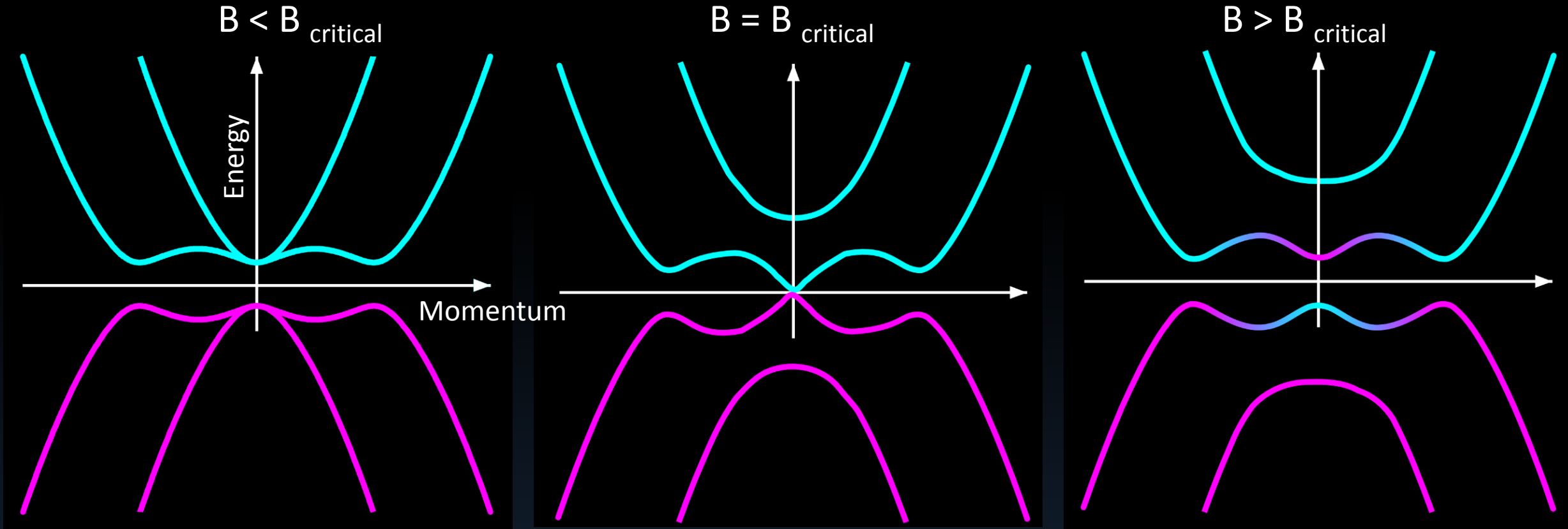
$$B > B_{\text{critical}}$$



← TOPOLOGICALLY DISTINCT
Number of crossing different in parity →



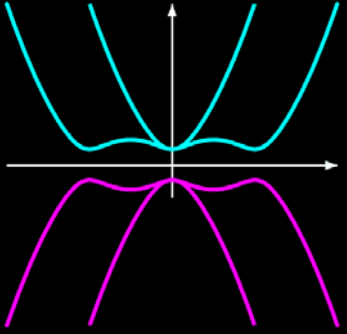
SOI + Magnetic field + superconductivity



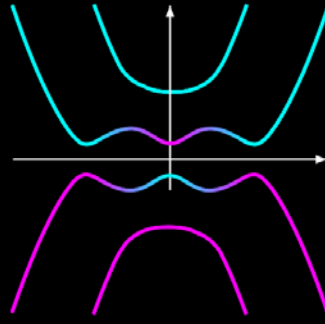
Y. Oreg et al. PRL(2010); R. M. Lutchyn et al PRL (2010);

Topology & bandstructure in 1D

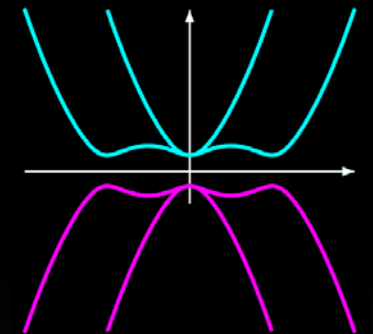
Non-Inverted band structure



Inverted band structure



Non-Inverted band structure



TRIVIAL

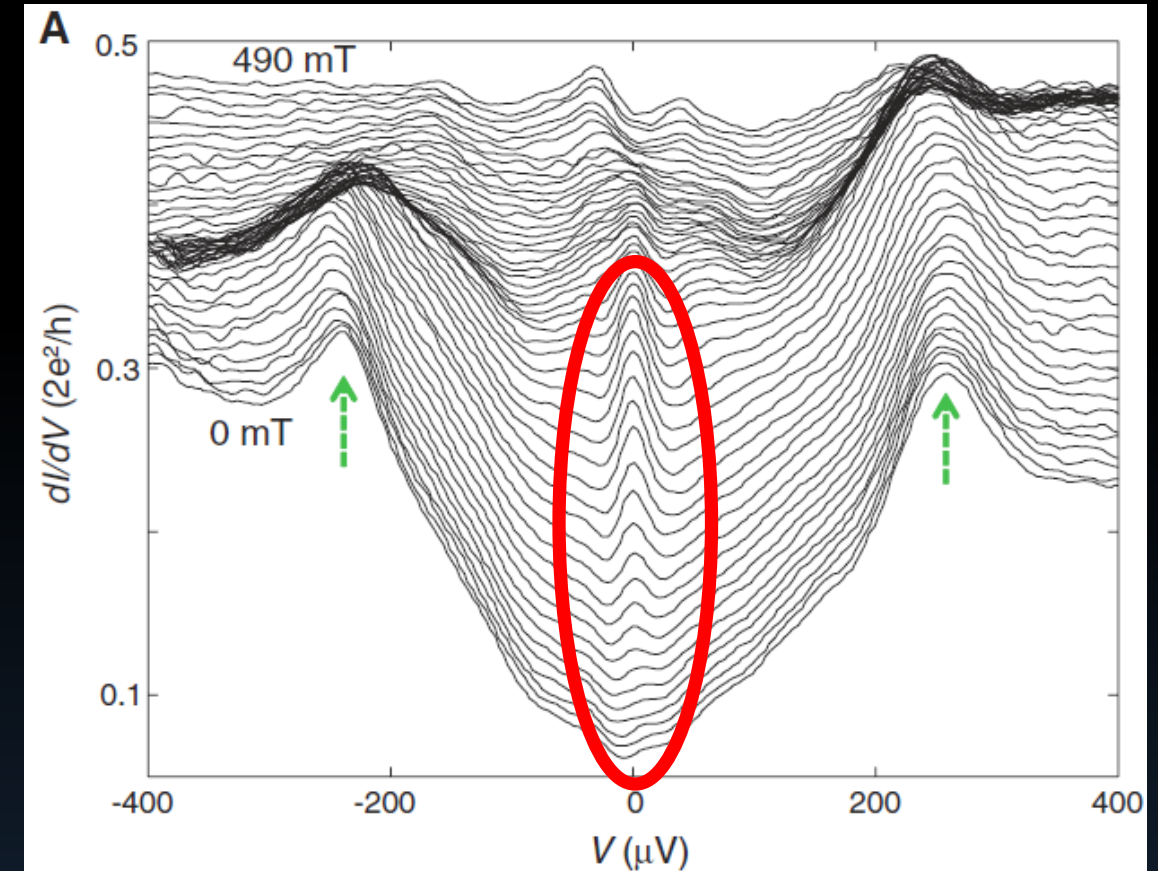
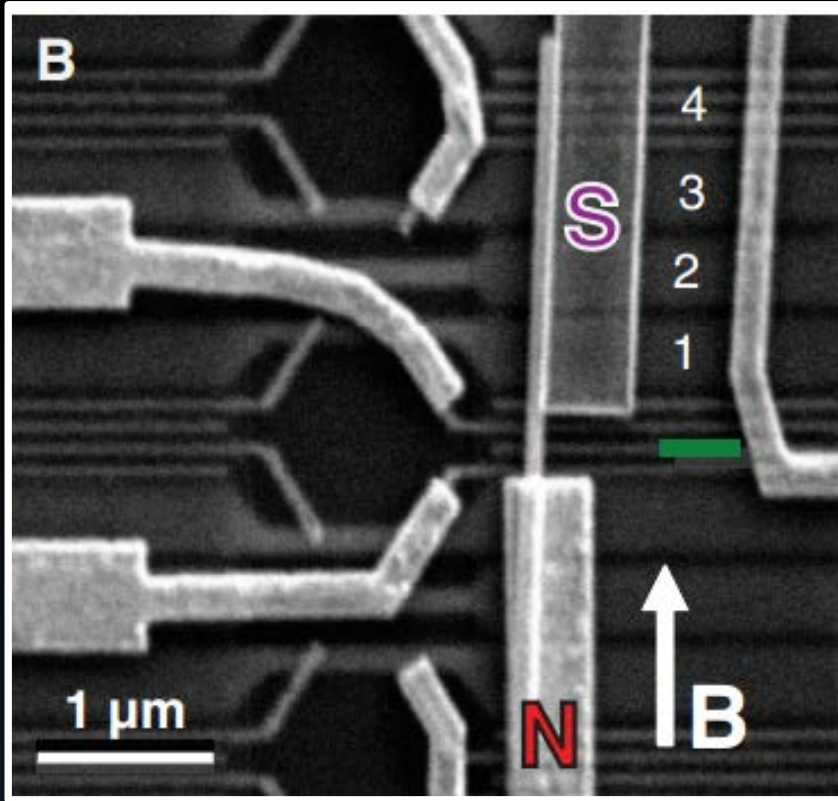
TOPOLOGICAL

TRIVIAL

Majorana
Edge States

Majorana wires

Zero bias peak in tunneling spectroscopy



Rokhinson et al. Nat. Phys. (2012)

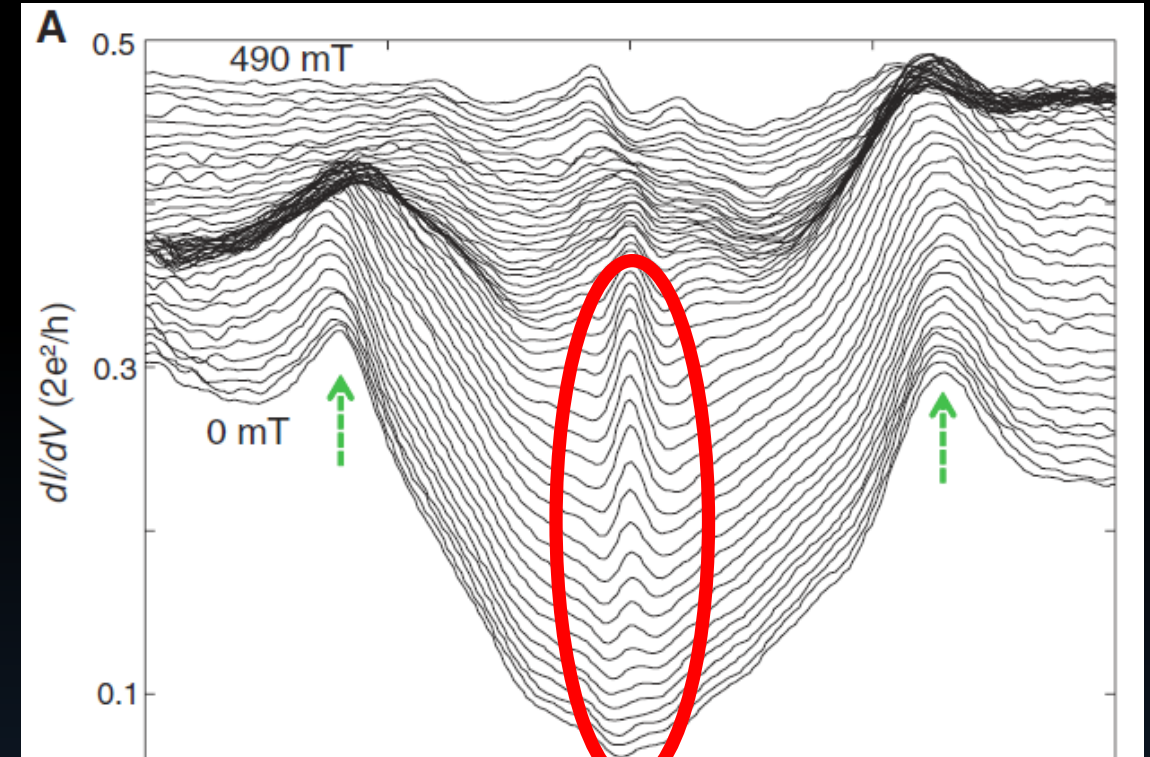
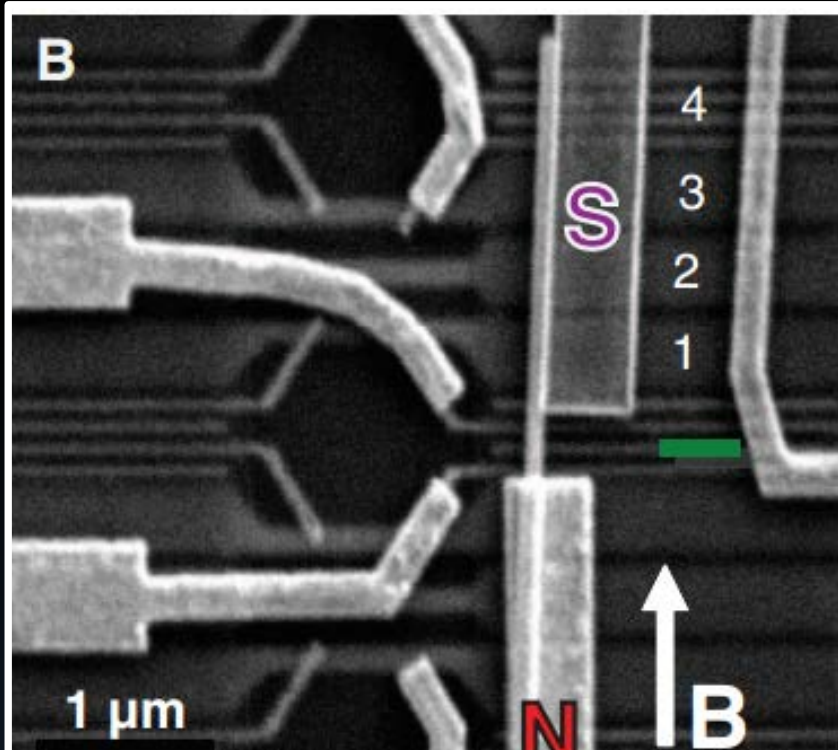
Das et al., Nat. Phys. (2012)

Mourik et al., Science (2012)

(Also: Deng et al. Nano Lett. (2012), van Harlinegen group and C. Marcus groups (2013), and others)

Majorana wires

Zero bias peak in tunneling spectroscopy



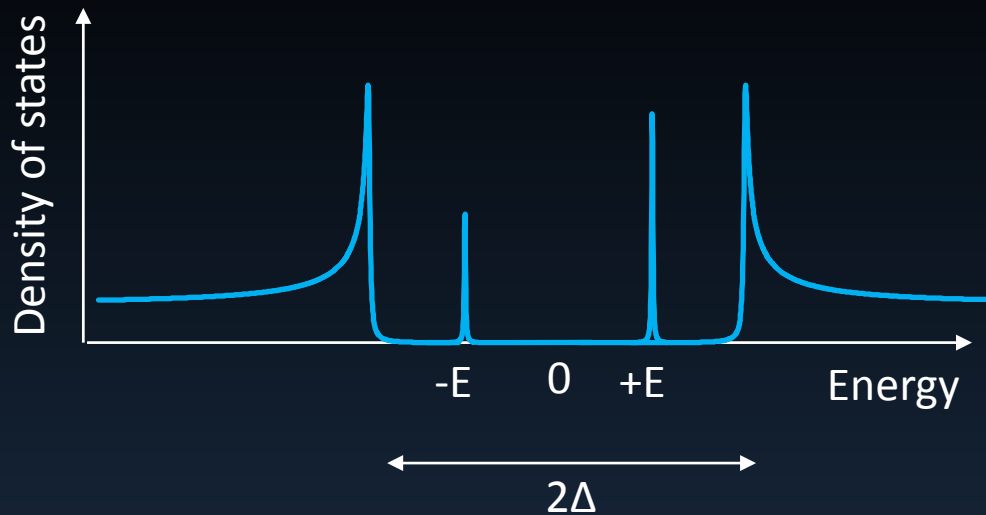
Hard to probe locally the wire ends
(Verify position of the Majorana modes)

Yu-Shiba-Rusinov states for a single atom

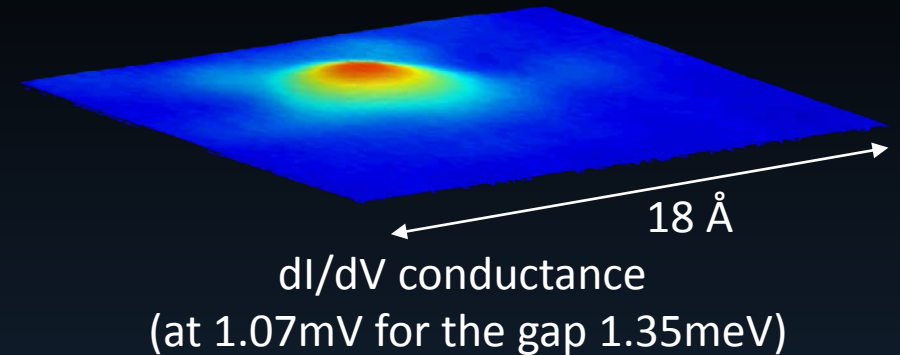
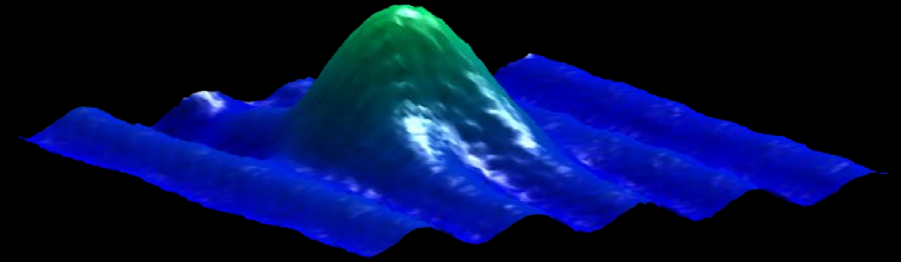
Classical spin in a superconductor $H = H_{BCS} + B \mathbf{S} \cdot \mathbf{s}$



s-wave superconductor



TOPOGRAPHY

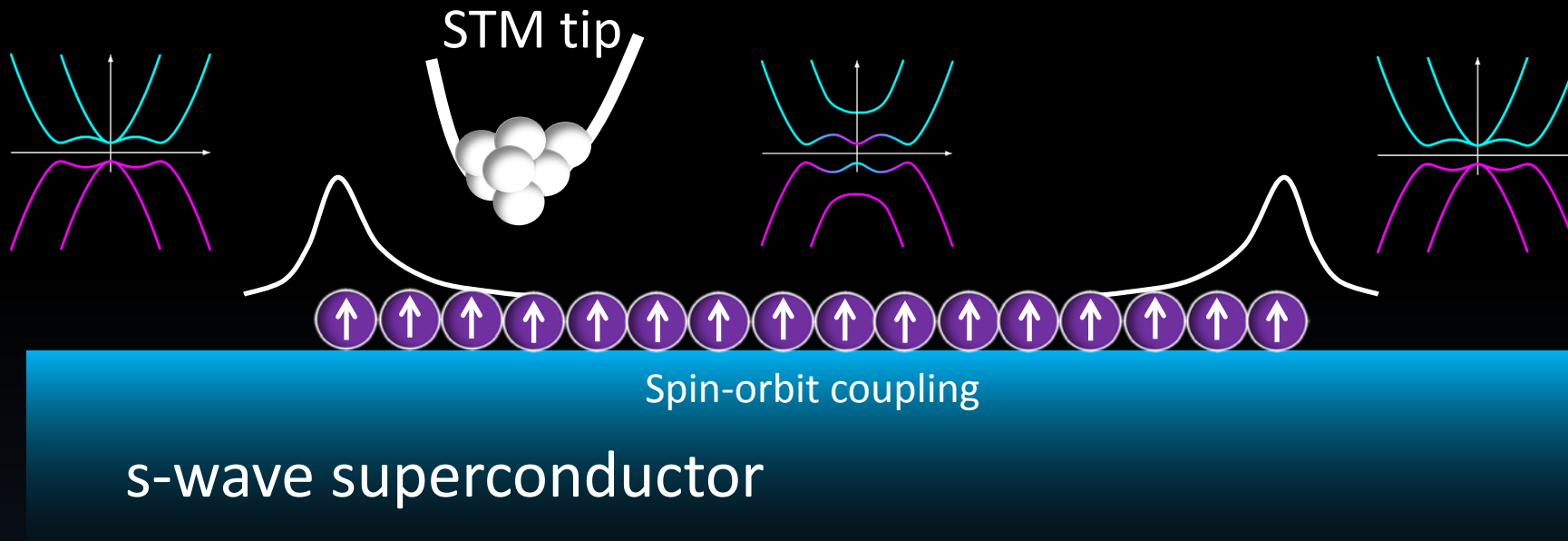


Mn, Gd on Nb Yazdani et al., Science (1997)

Cr, Mn on Pb, Ji et al., PRL (2008)

Yu APS (1965), Shiba PTP (1968), Rusinov JETP (1969), Balatsky et al RMP (2006)

Chain of magnetic atoms on the superconductor



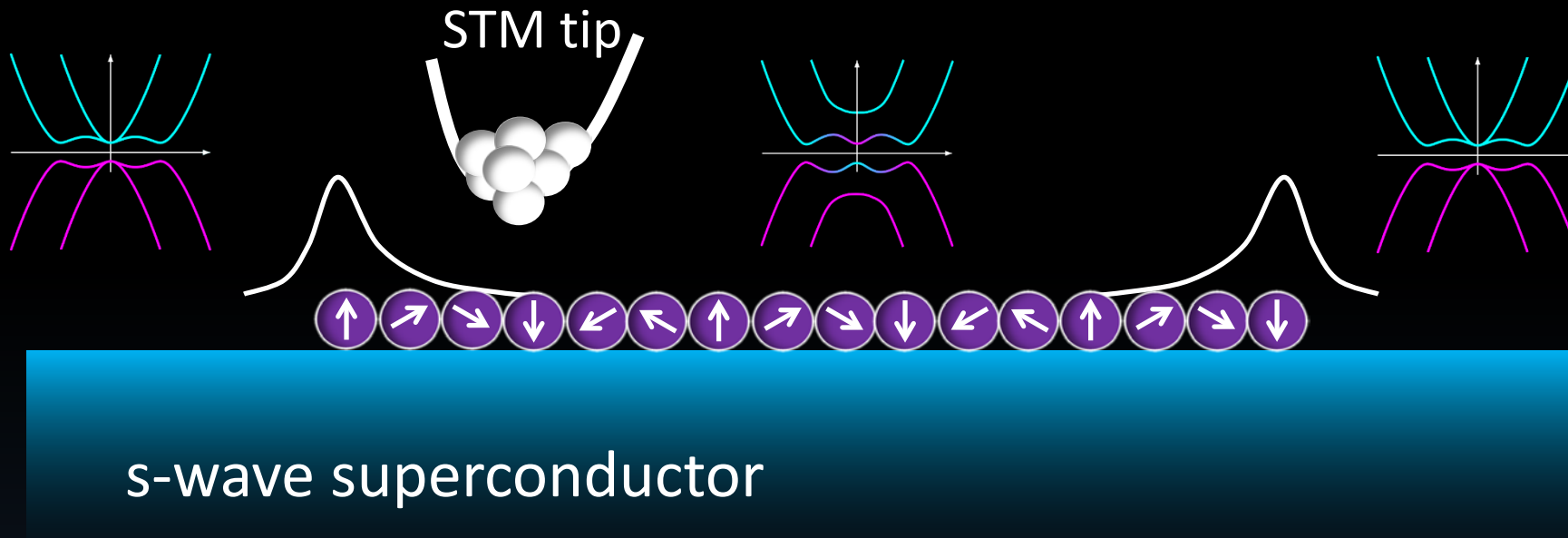
- Suitable for STM
- Can be disorder free



Magnetic atom

Magnetism + Superconductivity
Majorana proposals:
Choy et. al (PRB 2011)
Flensberg et. al (PRB 2011)
Martin and Morpurgo (PRB 2012)

Chain of magnetic atoms on the superconductor



- Suitable for STM
- Can be disorder free



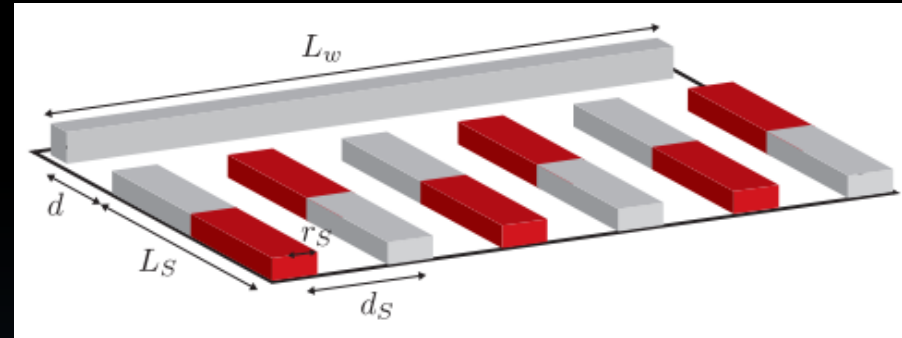
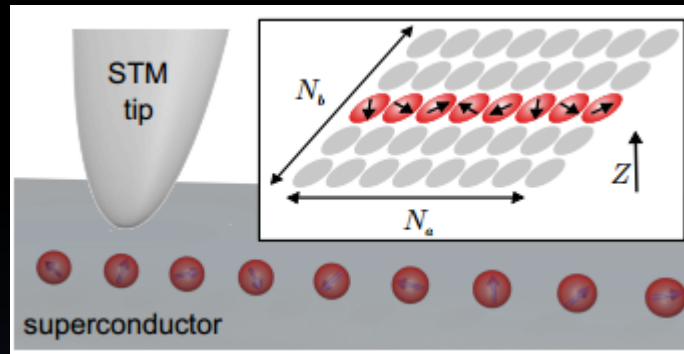
Magnetic atom

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Choy et. al (PRB 2011)
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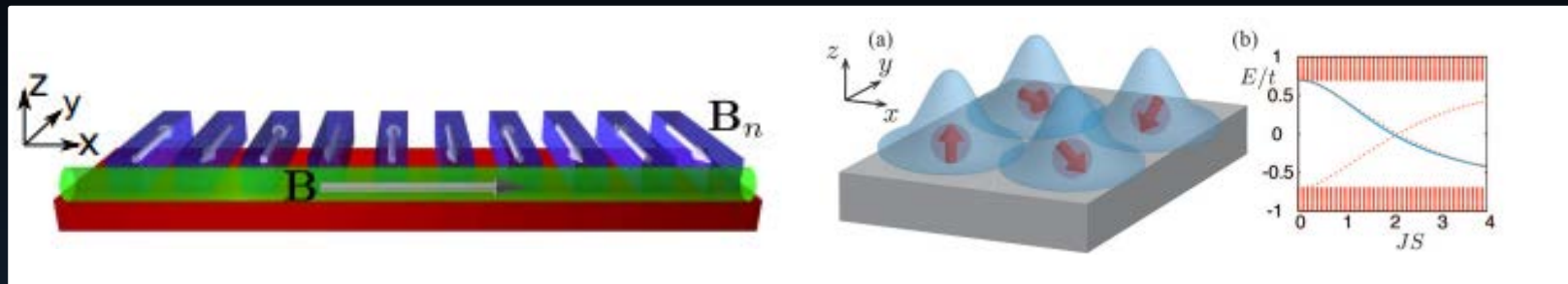
Majorana fermions and magnetic texture

Majorana fermions emerging from magnetic nanoparticles on a superconductor without spin-orbit coupling

T.-P. Choy, J. M. Edge, A. R. Akhmerov, and C. W. J. Beenakker
Instituut-Lorentz, Universiteit Leiden, P.O. Box 9506, 2300 RA Leiden, The Netherlands



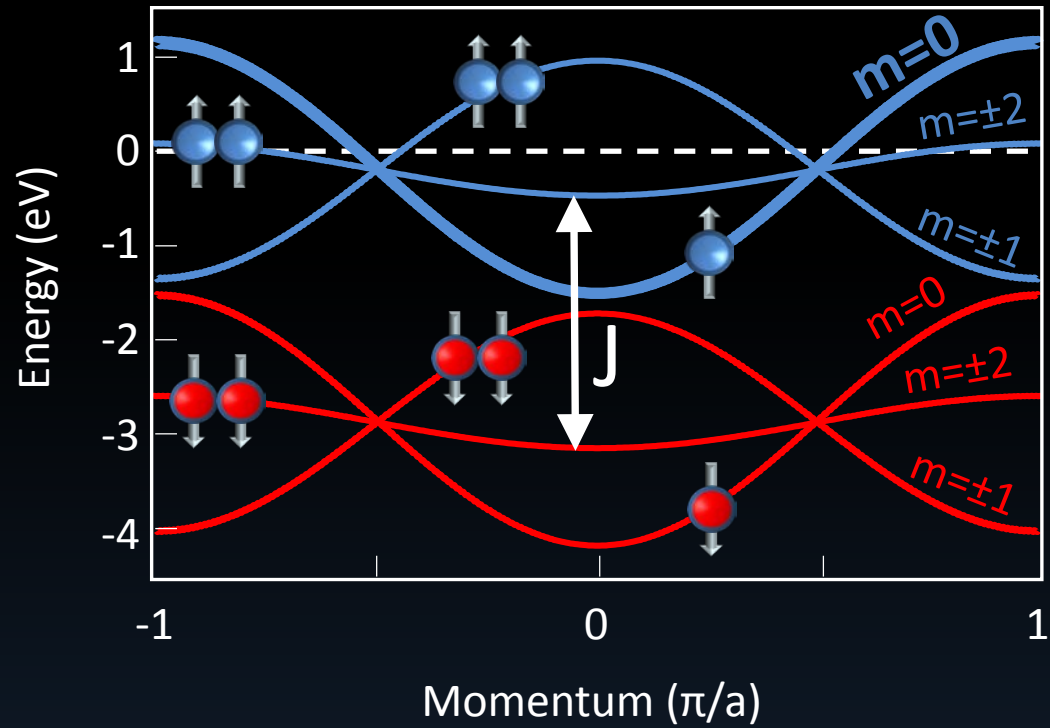
Nadj-Perge, Drozdov, Bernevig, Yazdani (PRB 2013) Kjaergaard, Wölms, Flensberg (PRB 2012)



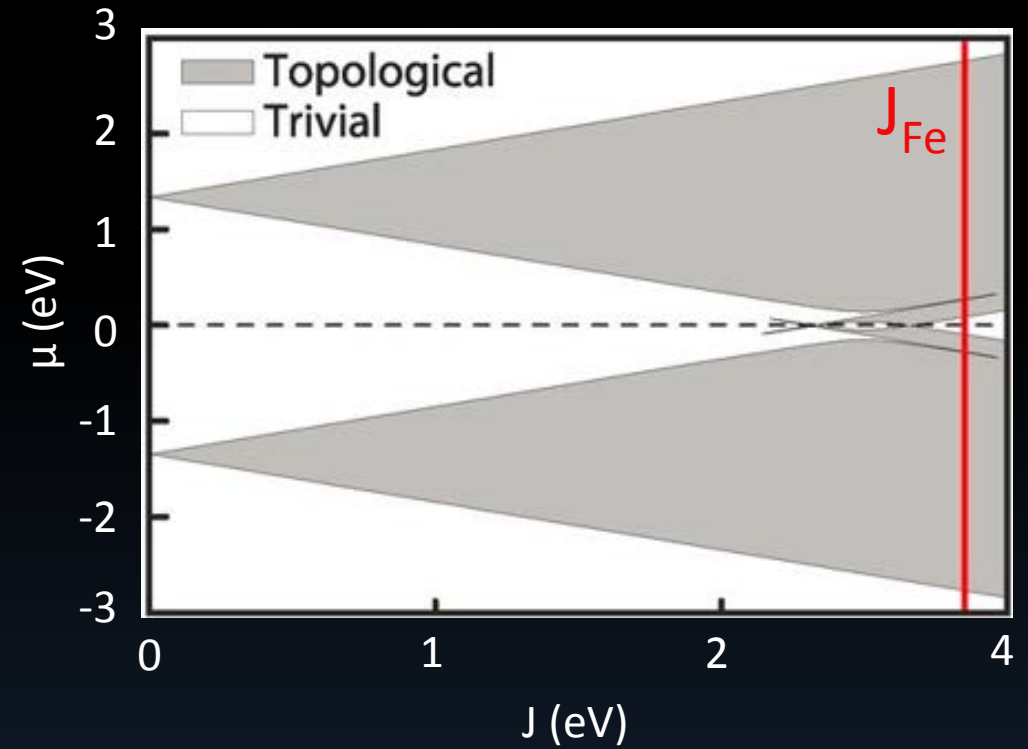
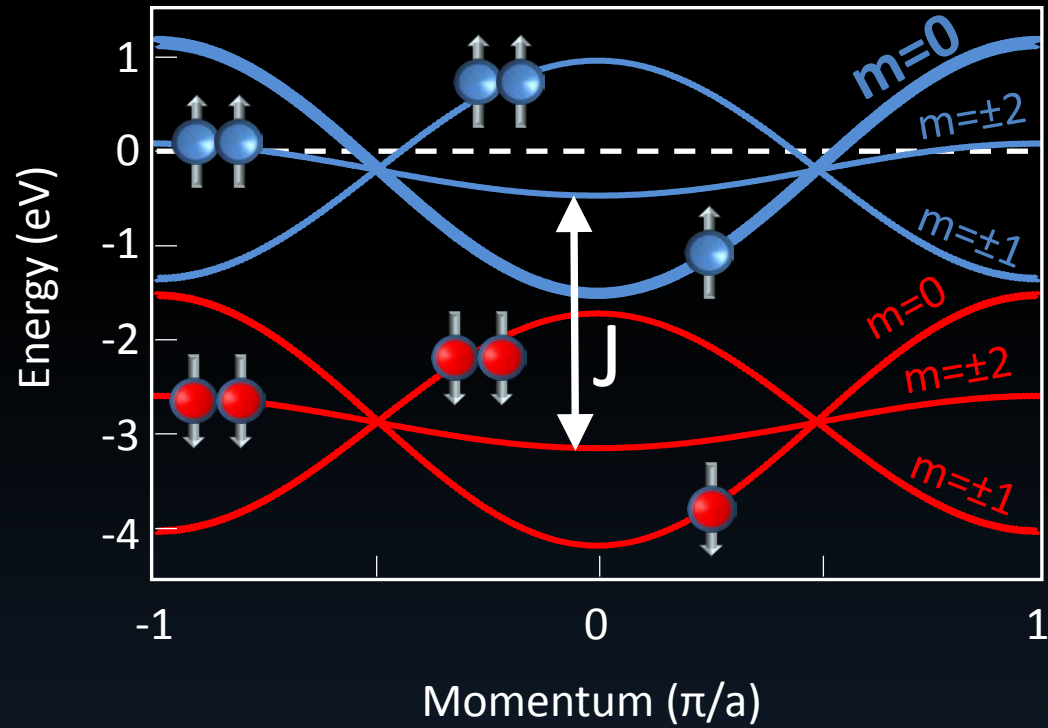
Klinovaja, Stano, Loss (PRL 2012)

Nakosai, Tanaka, Nagaosa (PRB 2013)

More than one band – Tight binding model

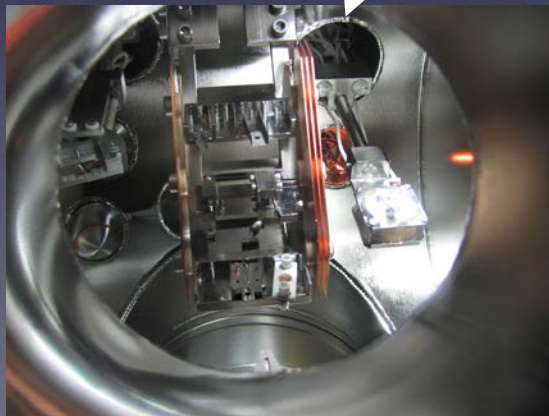
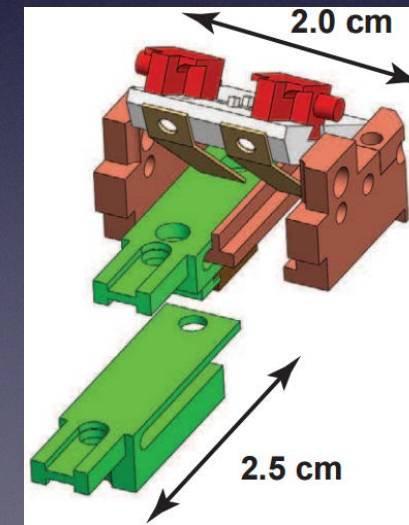
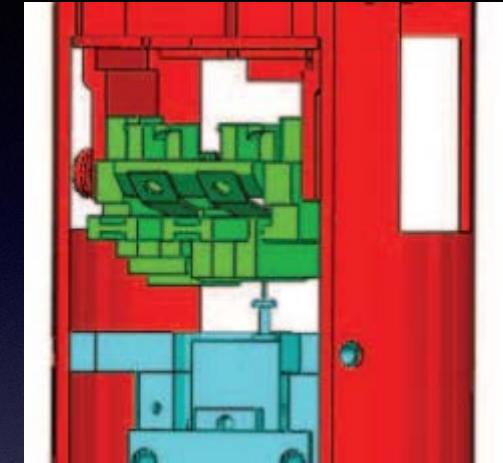
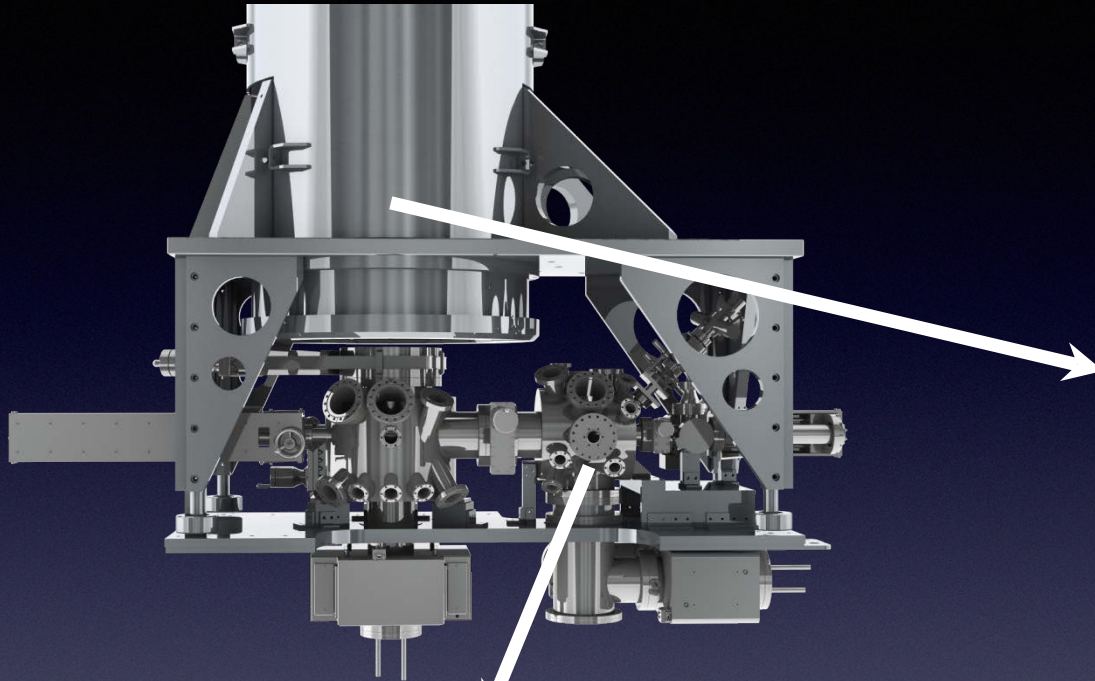


More than one band – Tight binding model



New Generation of High-Resolution STM at 1.4 K

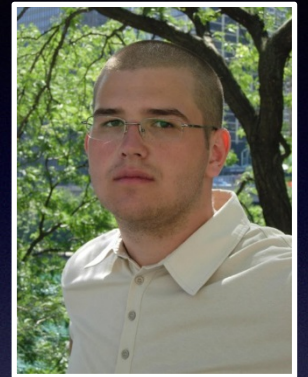
integrated STM/Growth/vector-field



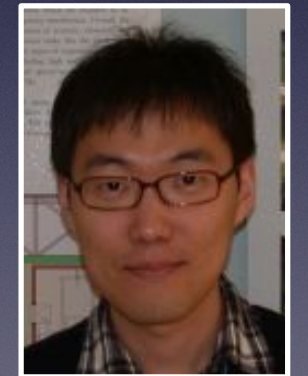
in situ growth capability

STM head: dual sample holder
Misra et al. Rev. Sci. Inst. (2013)

Assembled by:



Ilya Drozdov



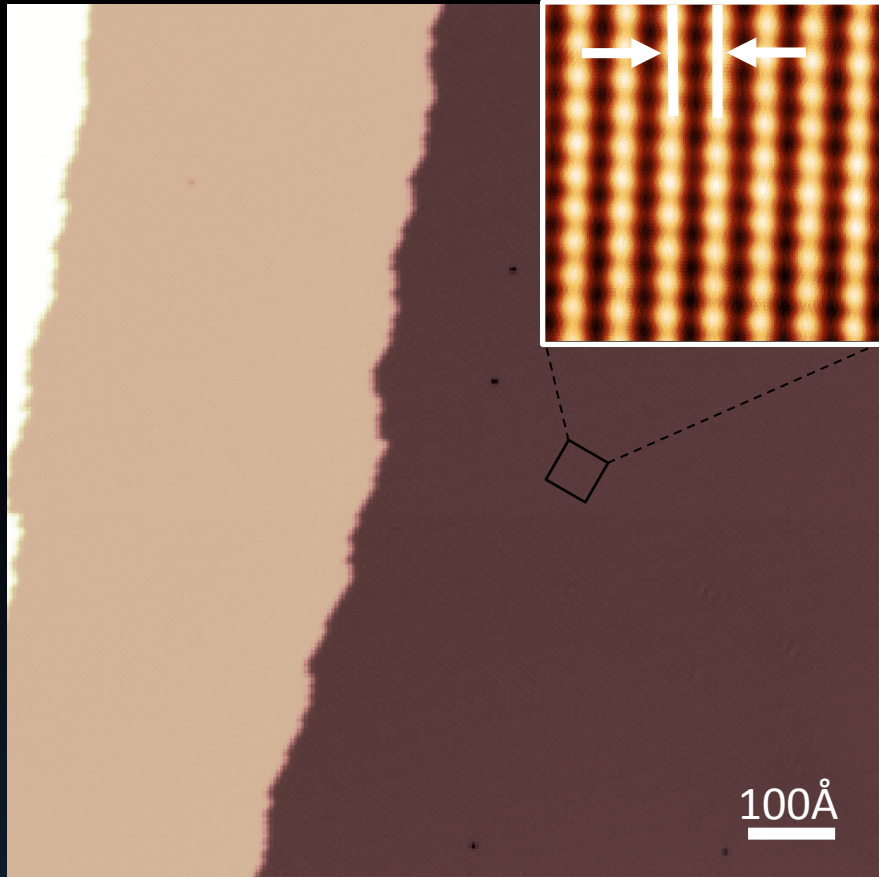
Jungpil Seo

Experimental requirements

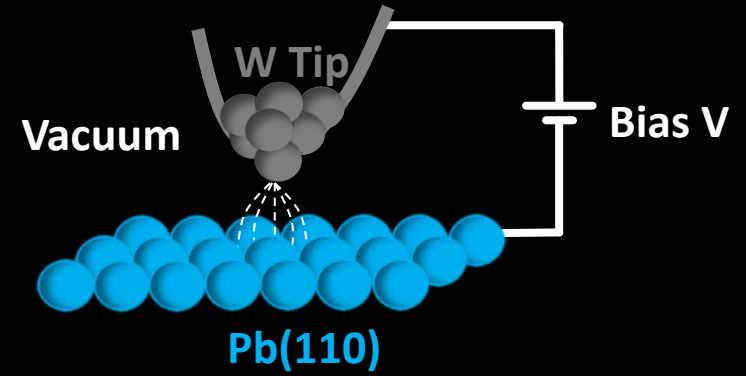
- 1) Atomically flat superconducting substrate
- 2) Magnetic atoms
- 3) Spin-orbit coupling (or spin texture)

Superconducting Pb (110) substrate

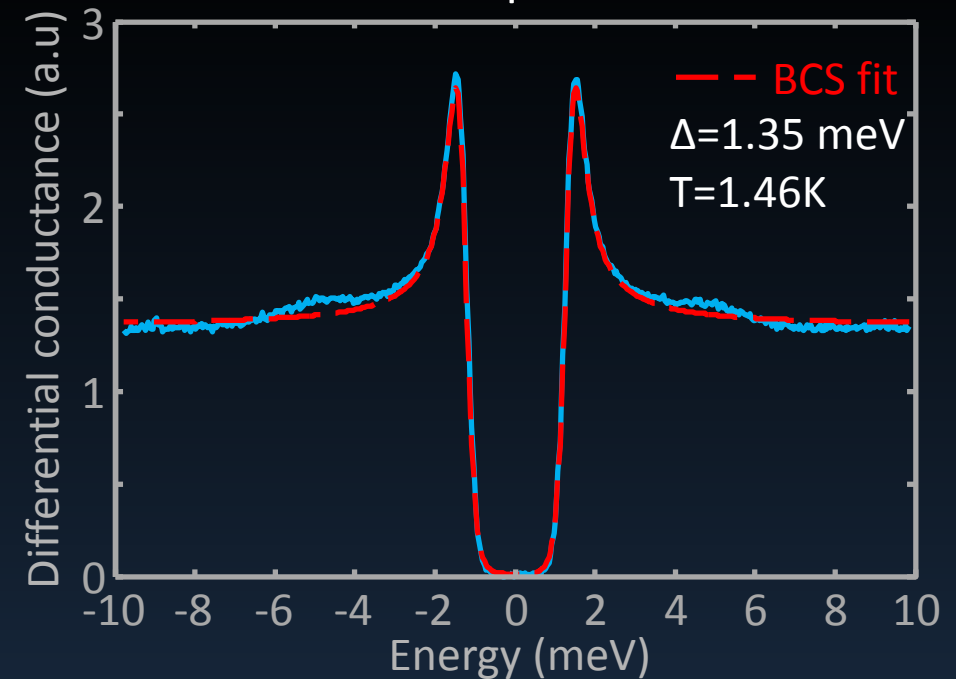
Topographic image – Pb(110) $a=4.95\text{\AA}$



$T_c=7.2\text{K}$, $\xi=830\text{\AA}$, $H_c=80\text{mT}$, $\lambda_L=370\text{\AA}$

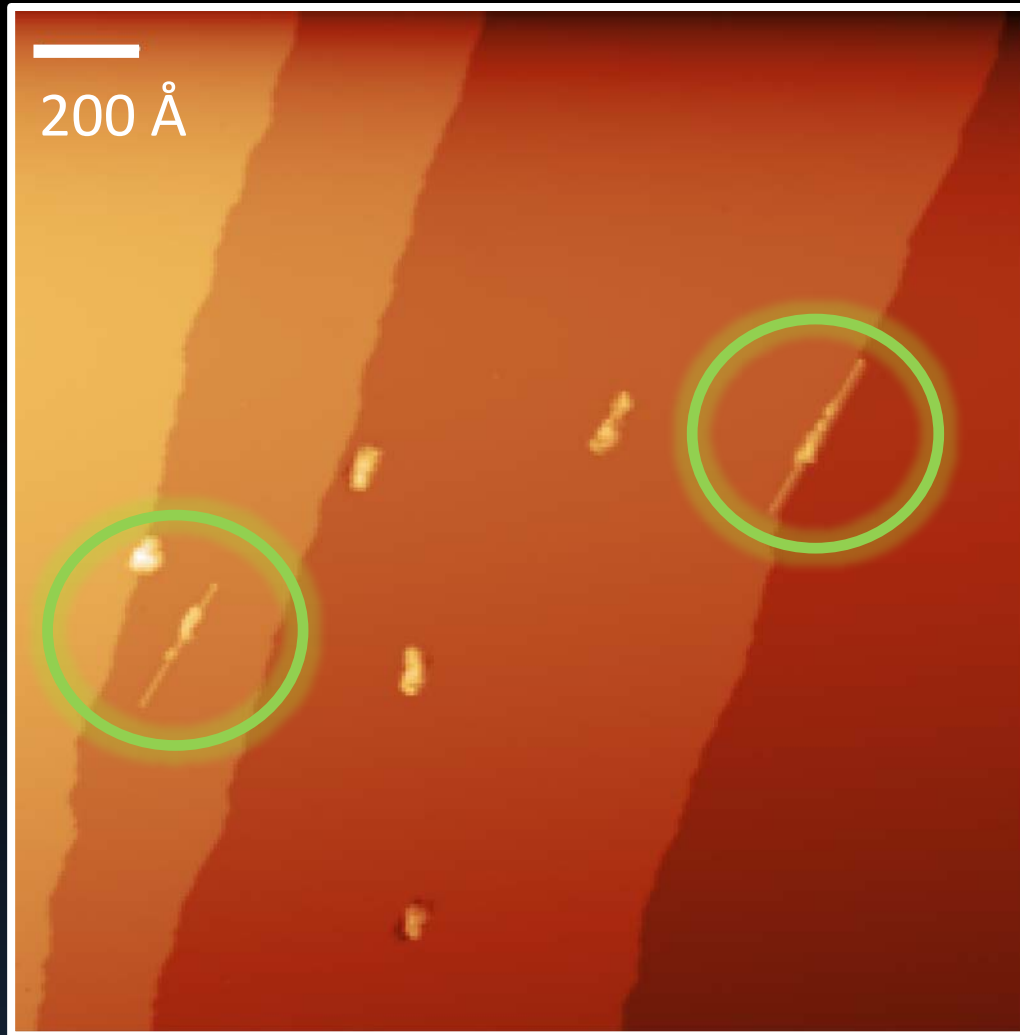


Point spectrum

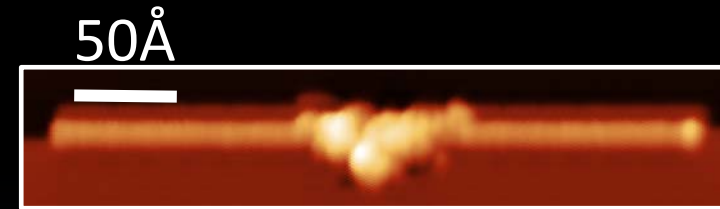


Fe atomic chain growth on Pb substrate

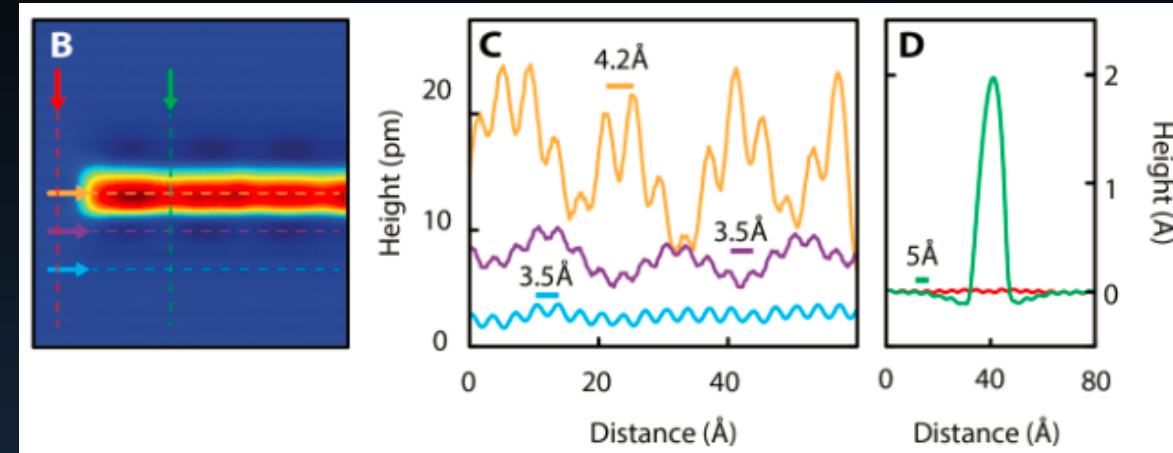
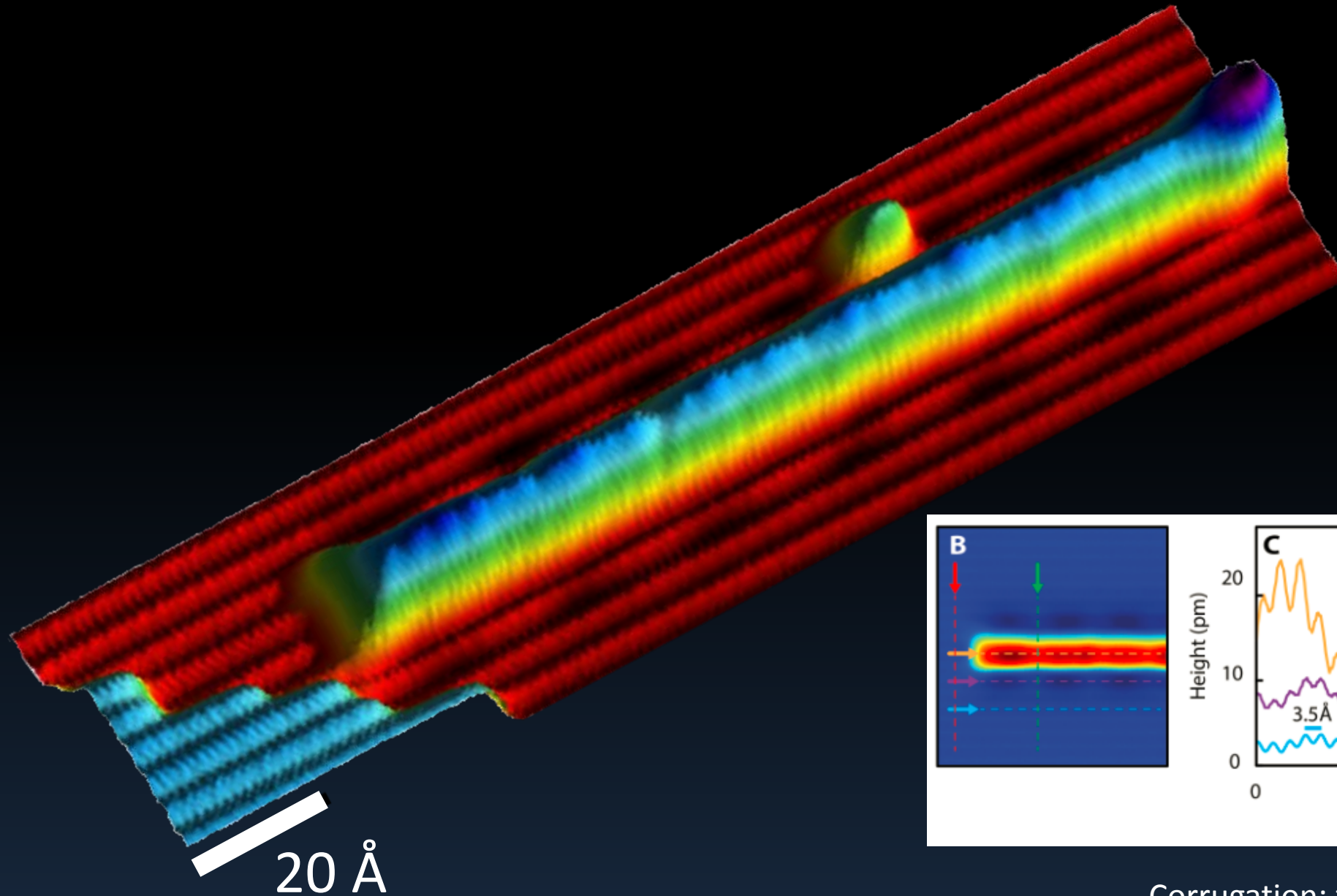
Topographic image



Total chain length up to 800 Å (~ 380 atoms)
“Clean” segments up to 150 Å (~ 70 atoms)



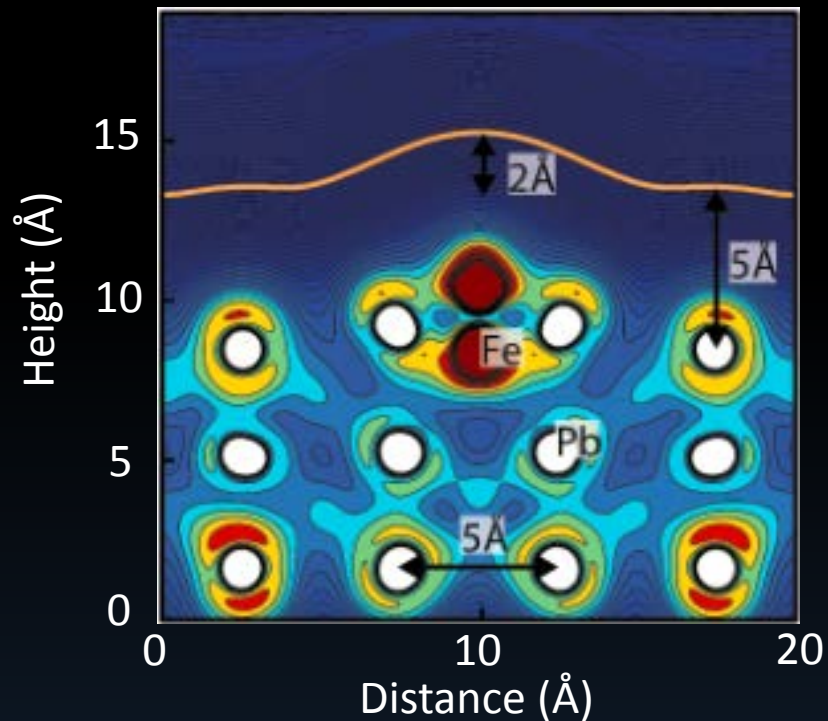
Single atom wide chains on Pb(110) substrate



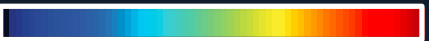
Corrugation: fitting Fe atoms onto Pb

Atomic chains on Pb(110) substrate – DFT

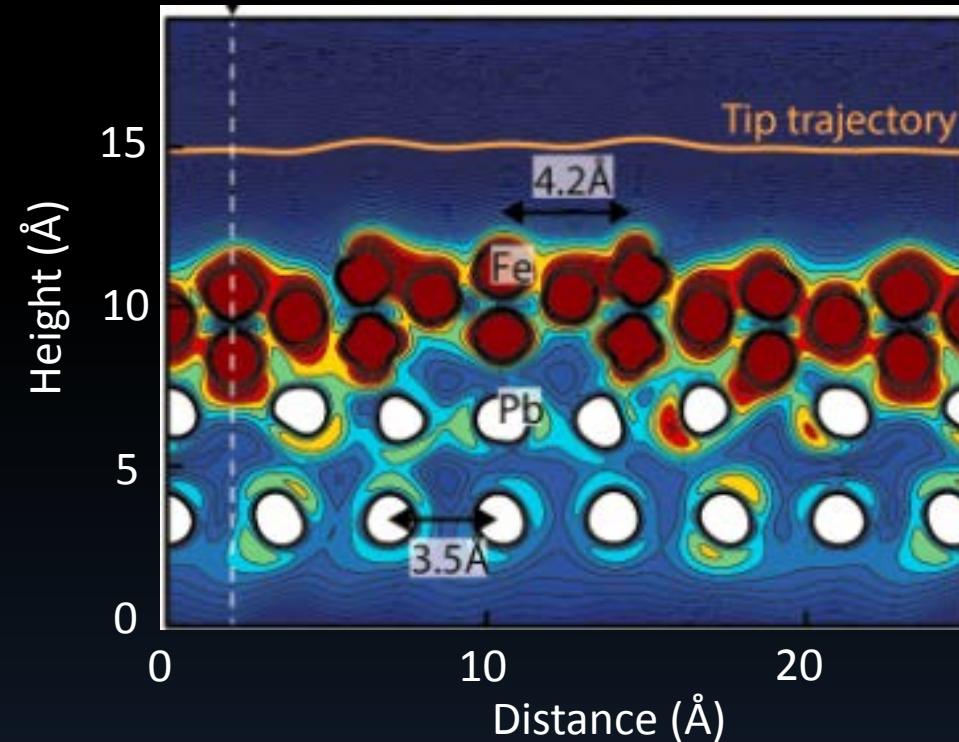
Cut across the chain



Charge density ($10^{-4}e/a_B^3$)

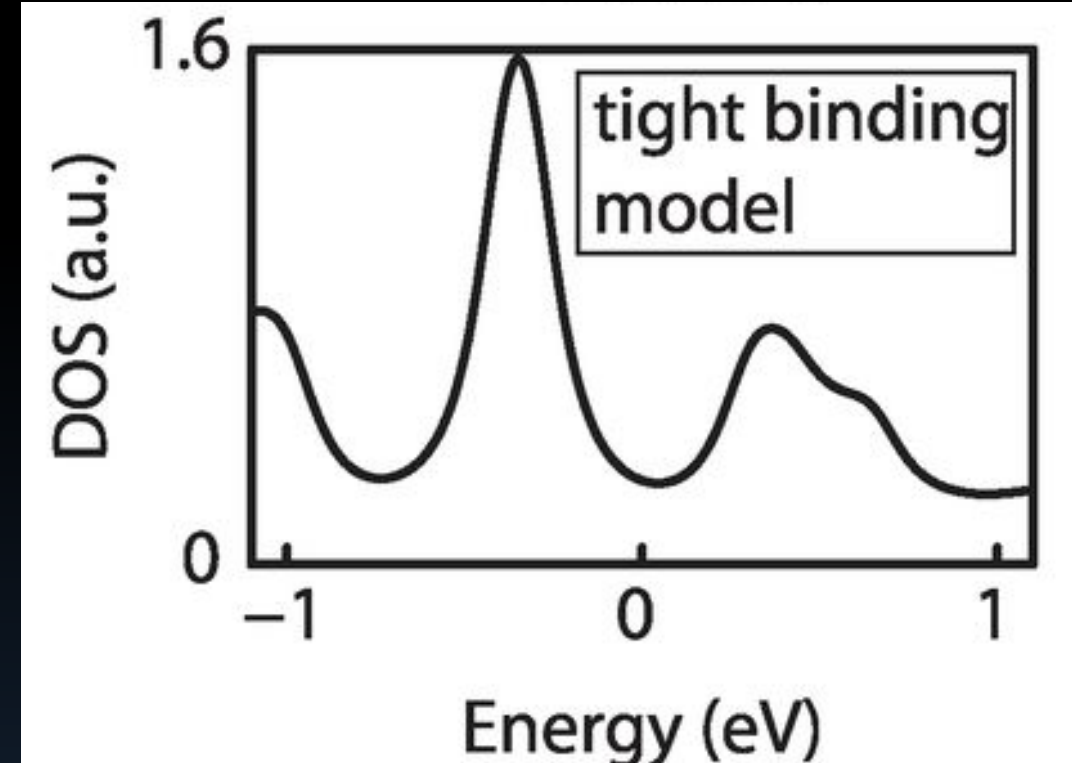
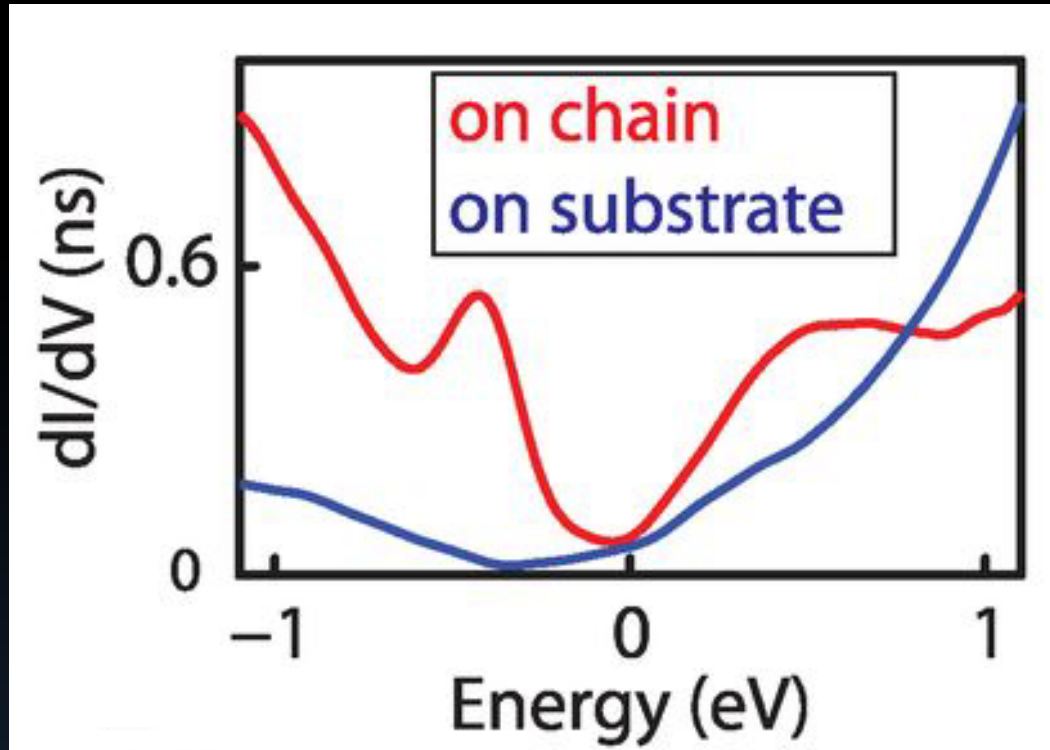
0  1.5

Cut along the middle of the chain

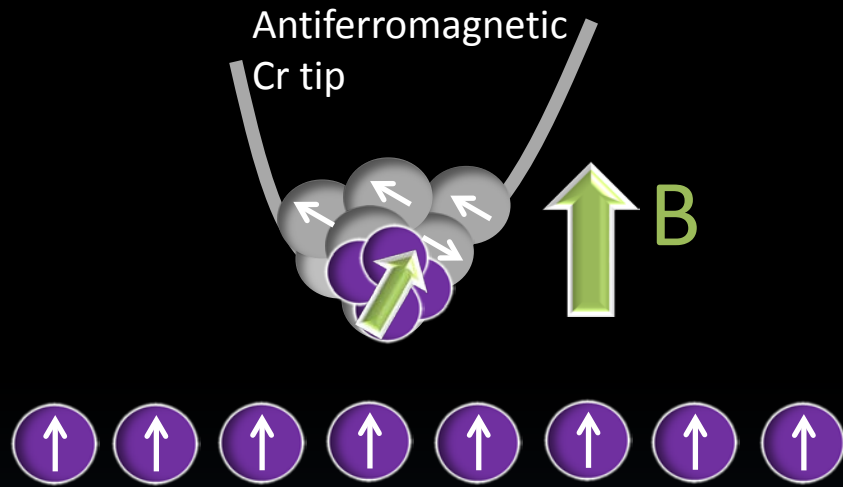


- 1) Chains form zig-zag structure
- 2) Corrugation periodicity reproduced
- 3) Expected height matches experiment

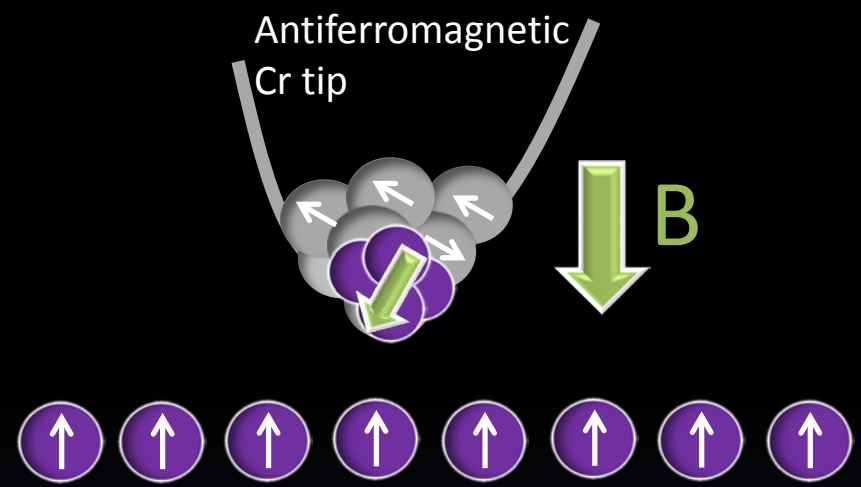
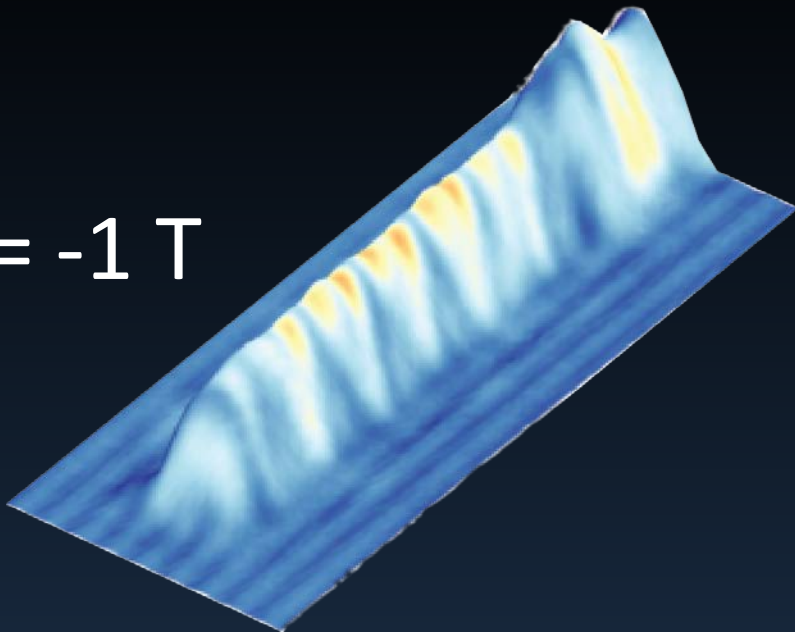
Point spectrum Experiment vs DFT modeling



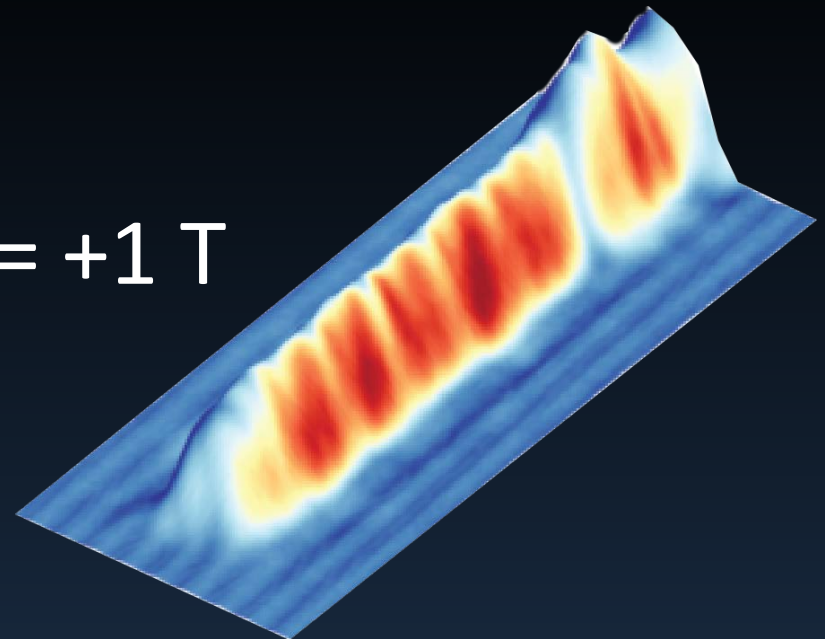
Spin-polarized measurements



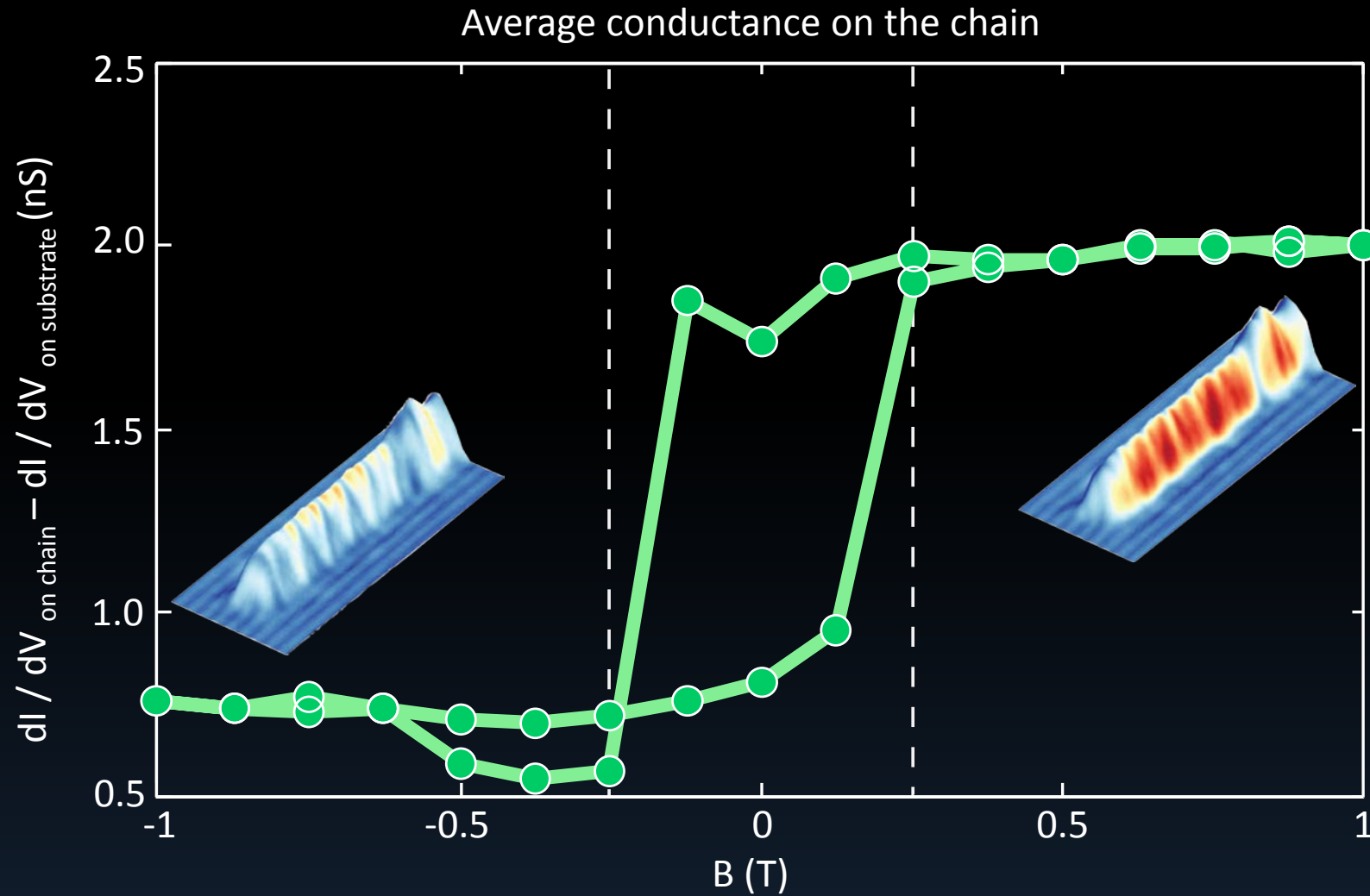
$B = -1 \text{ T}$



$B = +1 \text{ T}$



Fe chains on Pb(110): Spin-polarized measurements



Background subtracted

Most likely tip switching (at ± 0.25 T)

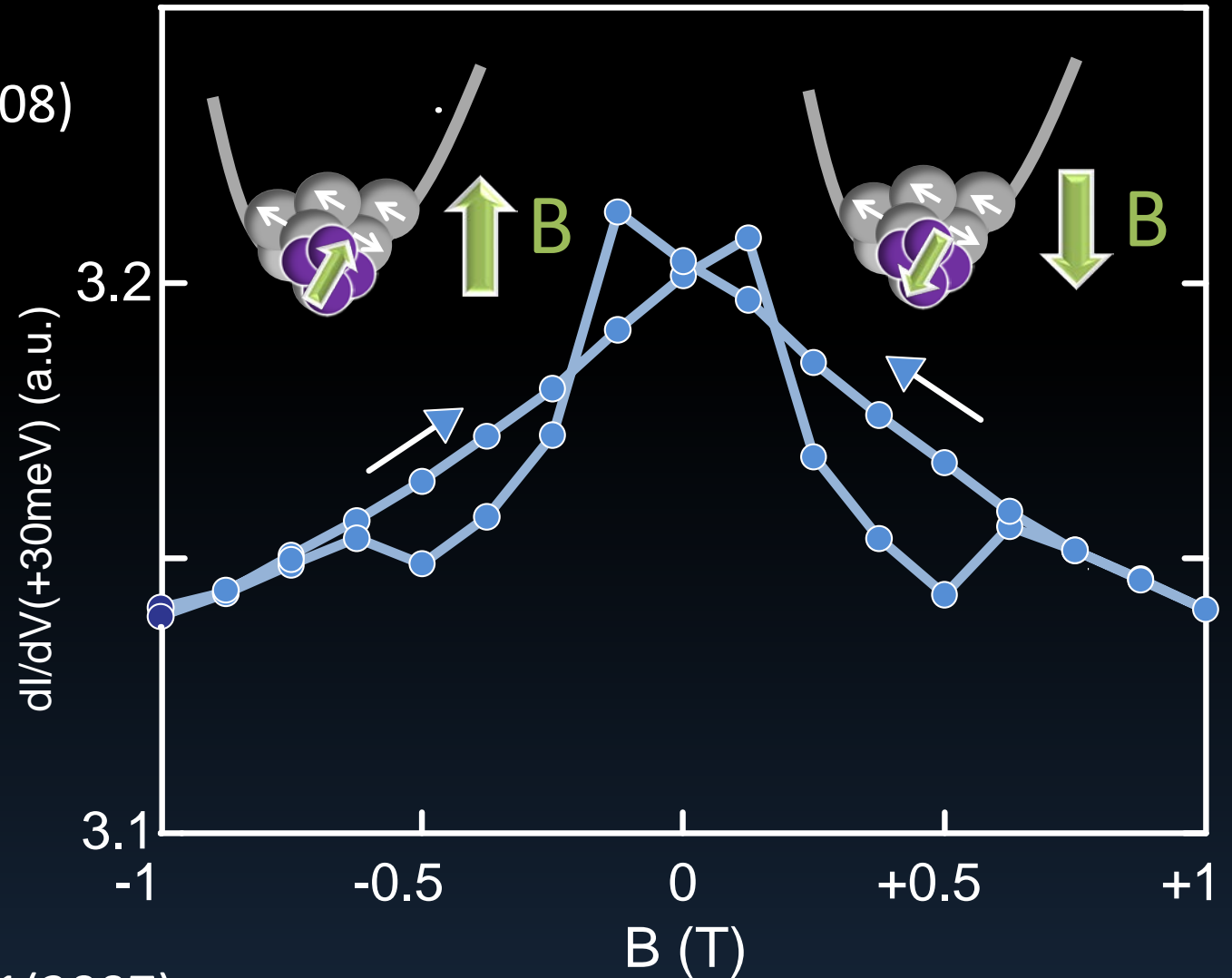
Spin-polarized tip on the Pb(110): Hints of spin-orbit coupling

Pb – Heavy element ($Z=82$, $A=204-208$)
Strong SOI expected
Symmetry broken at the surface

Experimental signature:




Tunneling suppressed when
Tip polarized out of plane
(Spins in plane)

Similar experiment in 2DEG GaAs:
Moser et al, Phys Rev. Lett. **99**, 056601(2007)



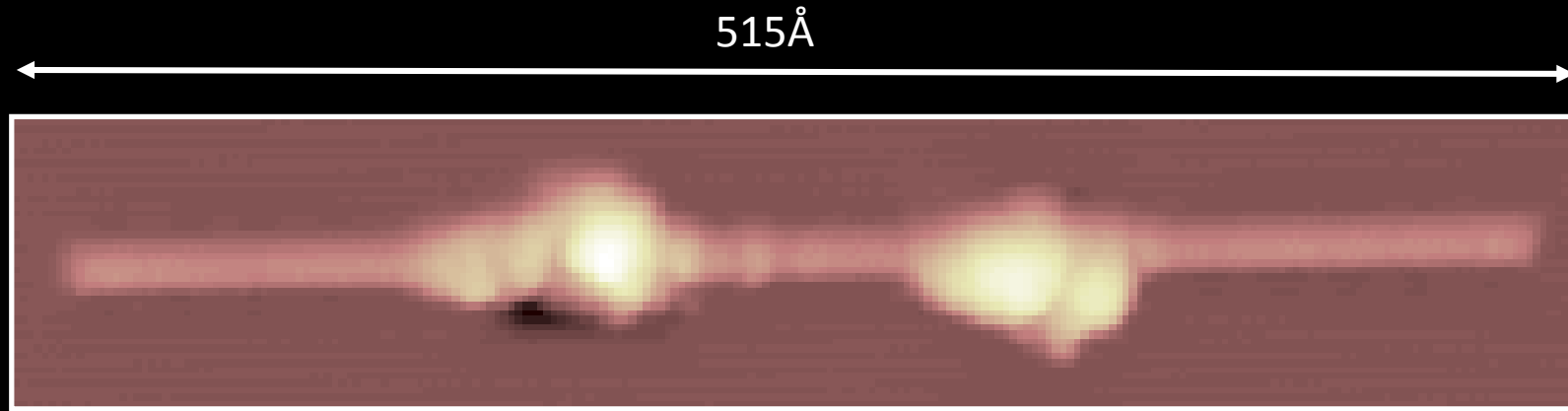
Consistent with strong SOI at the Pb surface

Experimental requirements

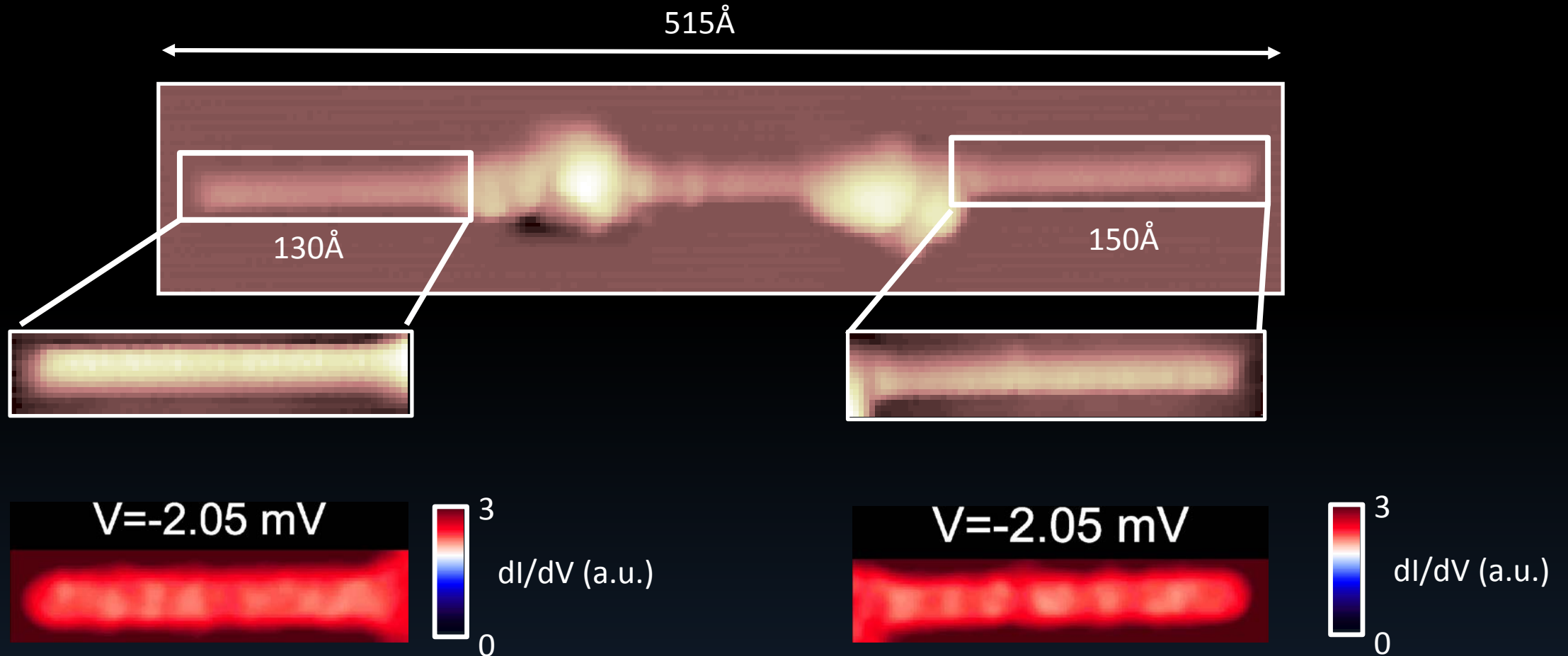
- 1) Atomically flat superconducting substrate 
- 2) Magnetic atoms (break spin degeneracy) 
- 3) Spin-orbit coupling in substrate (to enable p-wave pairing) 

HOW DO STATES INSIDE SUPERCONDUCTING GAP LOOK LIKE?????

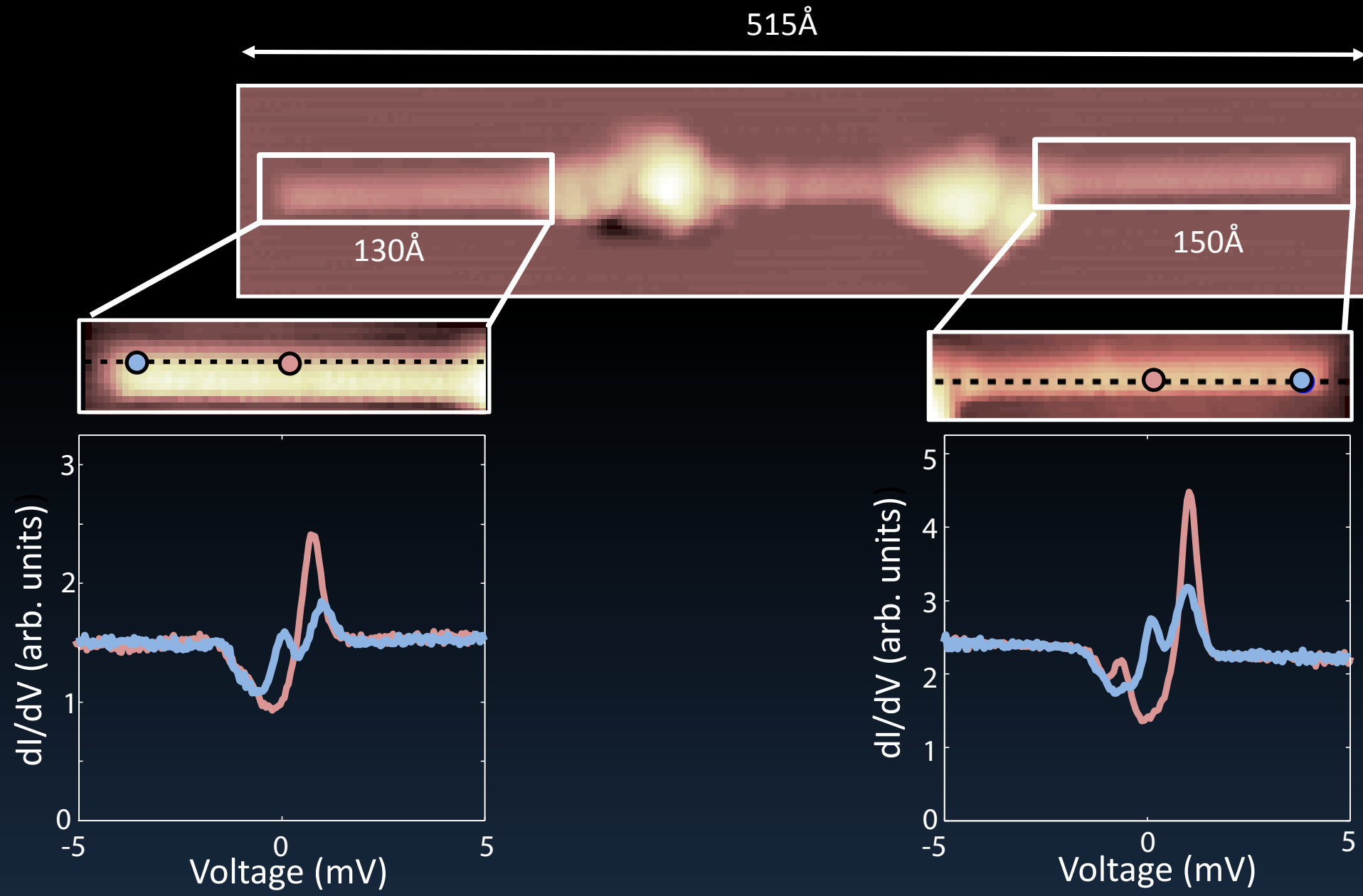
Spectroscopy of an atomic chain



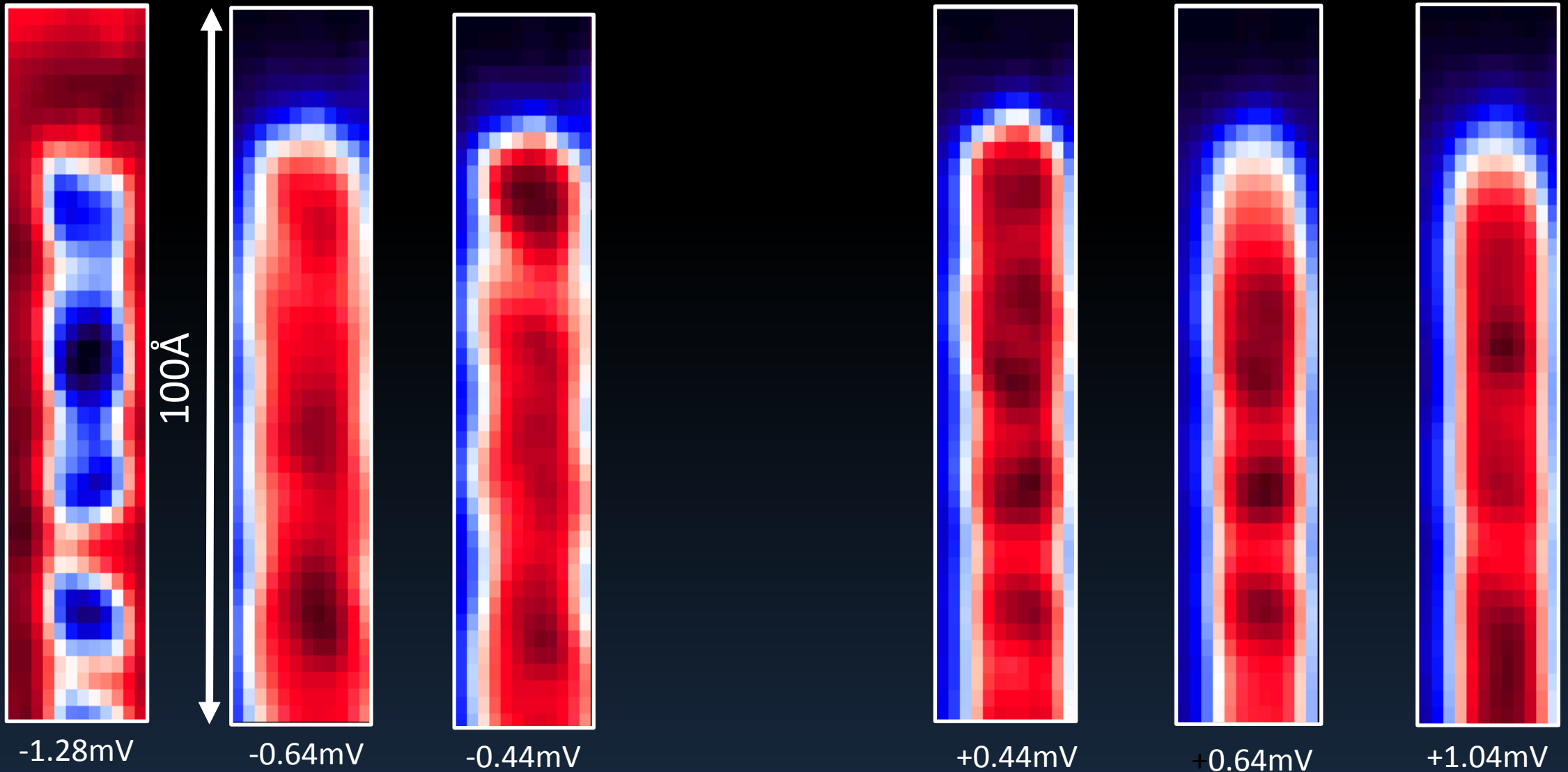
Spectroscopy of an atomic chain



Spectroscopy of an atomic chain

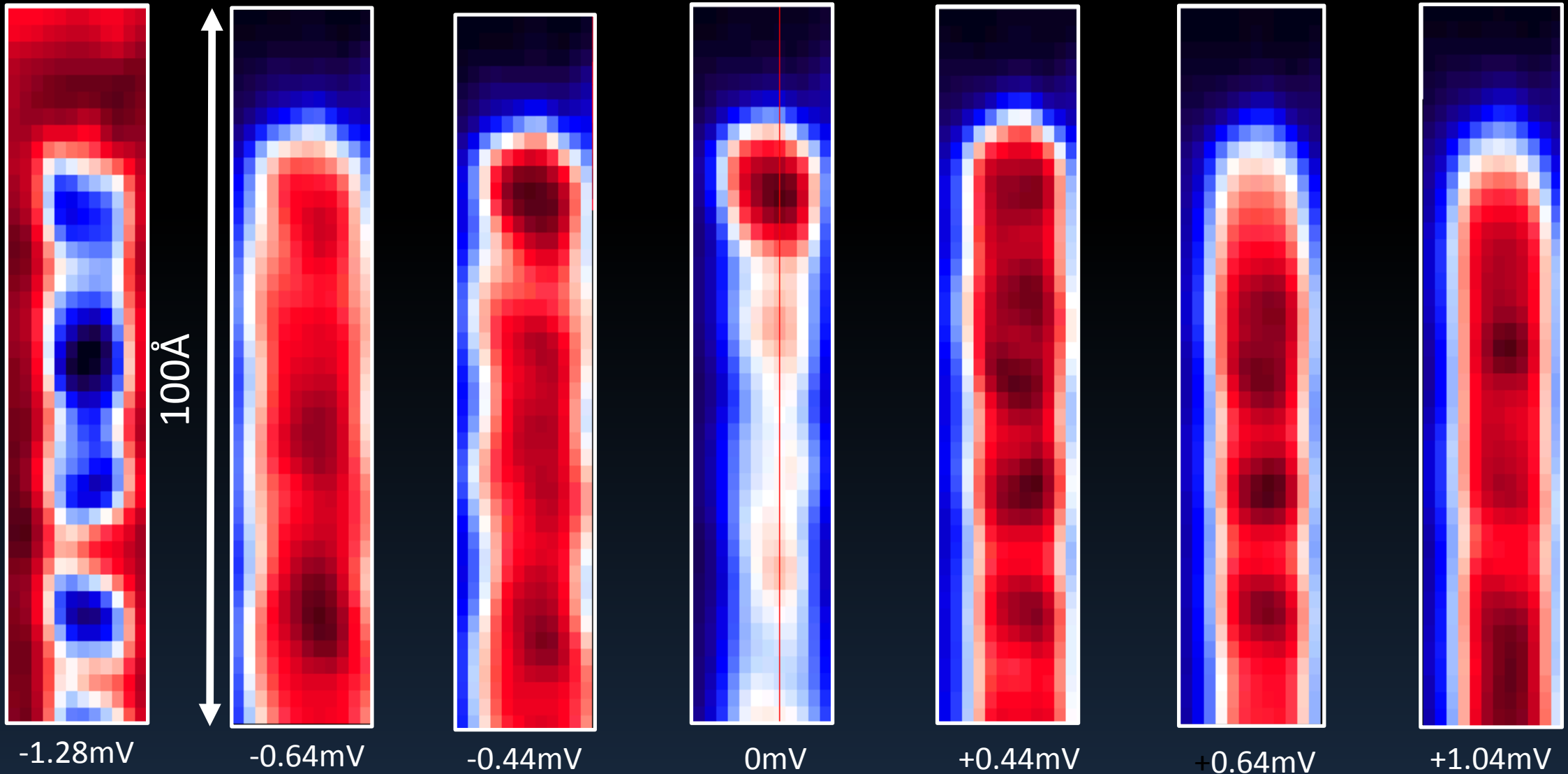


Spatial extent of the density of the states: another example



Spatial extent of the density of the states: another example

Zero bias peak feature localized on the scale of a 1nm

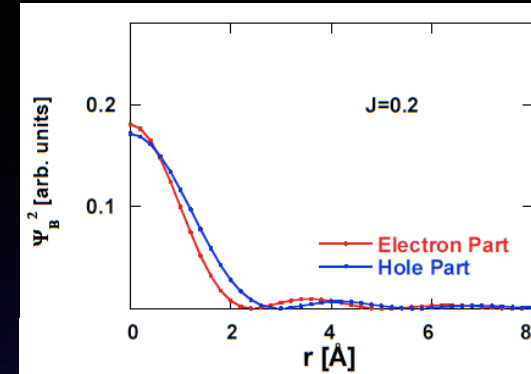


Localization length of MQP in an atomic chain

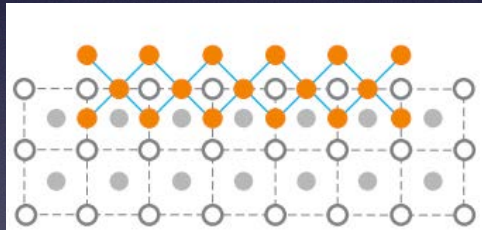
Recall Shiba states

$$\psi(r) \propto \frac{2\pi e^{-r/\xi}}{k_F r} \quad |\psi(r)|^2 \sim 1/r^2$$

$\xi \sim 500-1000 \text{ \AA}$ $\lambda_F/2 = 2-3 \text{ \AA}$

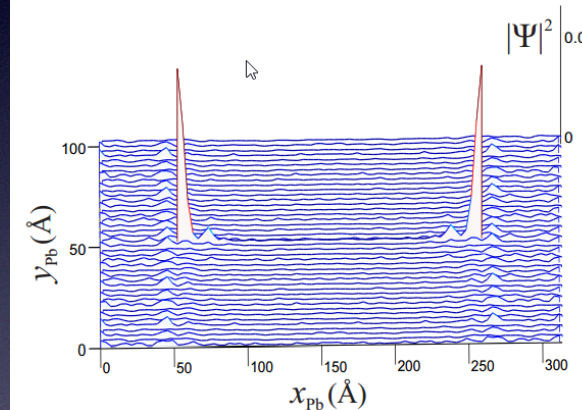


Realistic model of imbedded Fe chain
calculations show atomic scale localization of
Majorana



(D chain)

J. Li, H. Chen et al, Phys.
Rev. B **90**, 235433 (2014)



Renormalization of v_F due to d-band/Shiba hybridization

PRL **114**, 106801 (2015)

PHYSICAL REVIEW LETTERS

week ending
13 MARCH 2015

Strong Localization of Majorana End States in Chains of Magnetic Adatoms

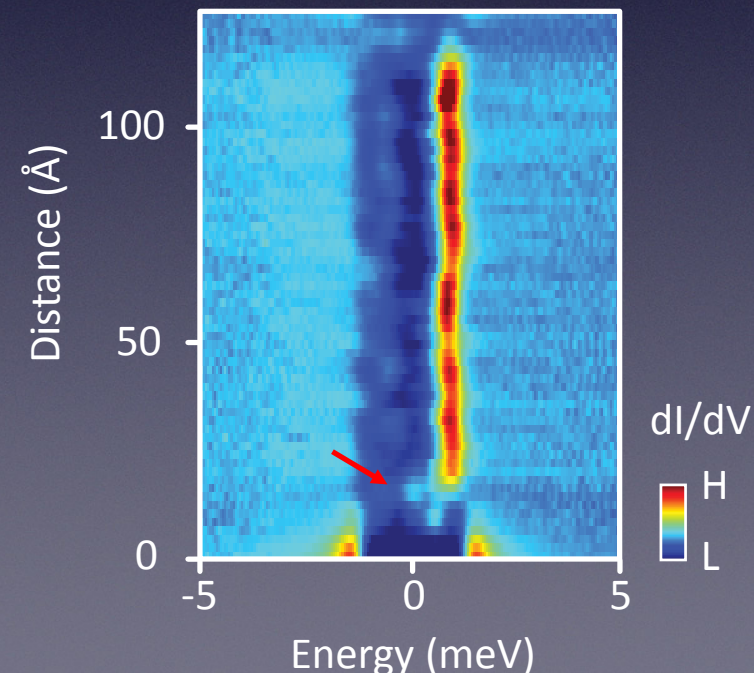
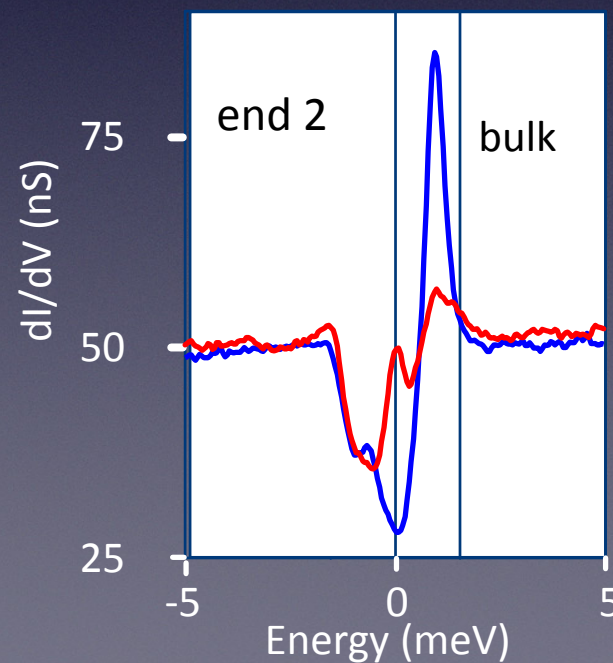
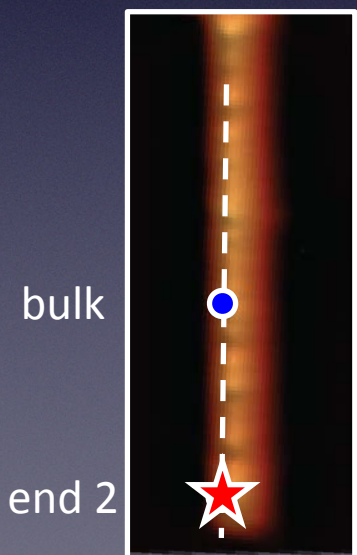
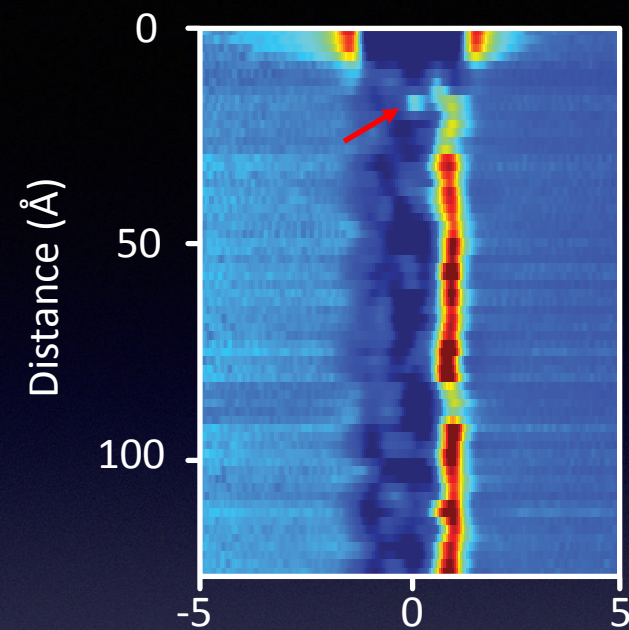
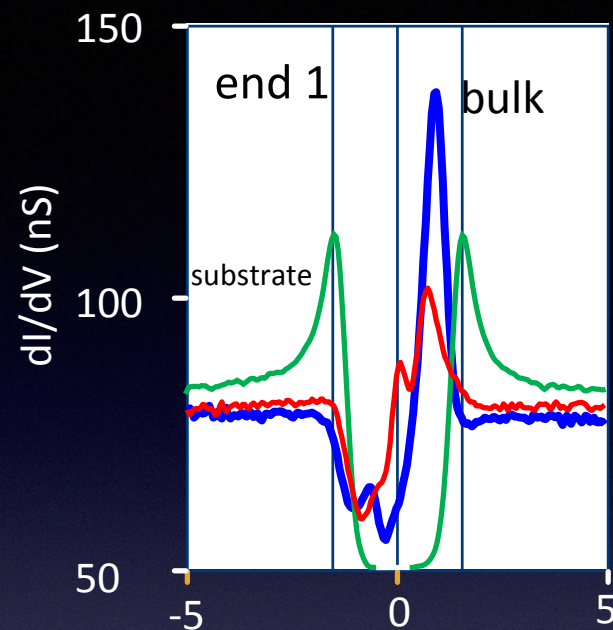
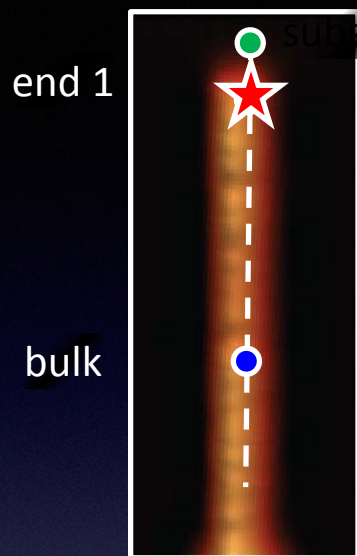
Yang Peng,¹ Falko Pientka,¹ Leonid I. Glazman,² and Felix von Oppen¹

¹Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, 14195 Berlin, Germany

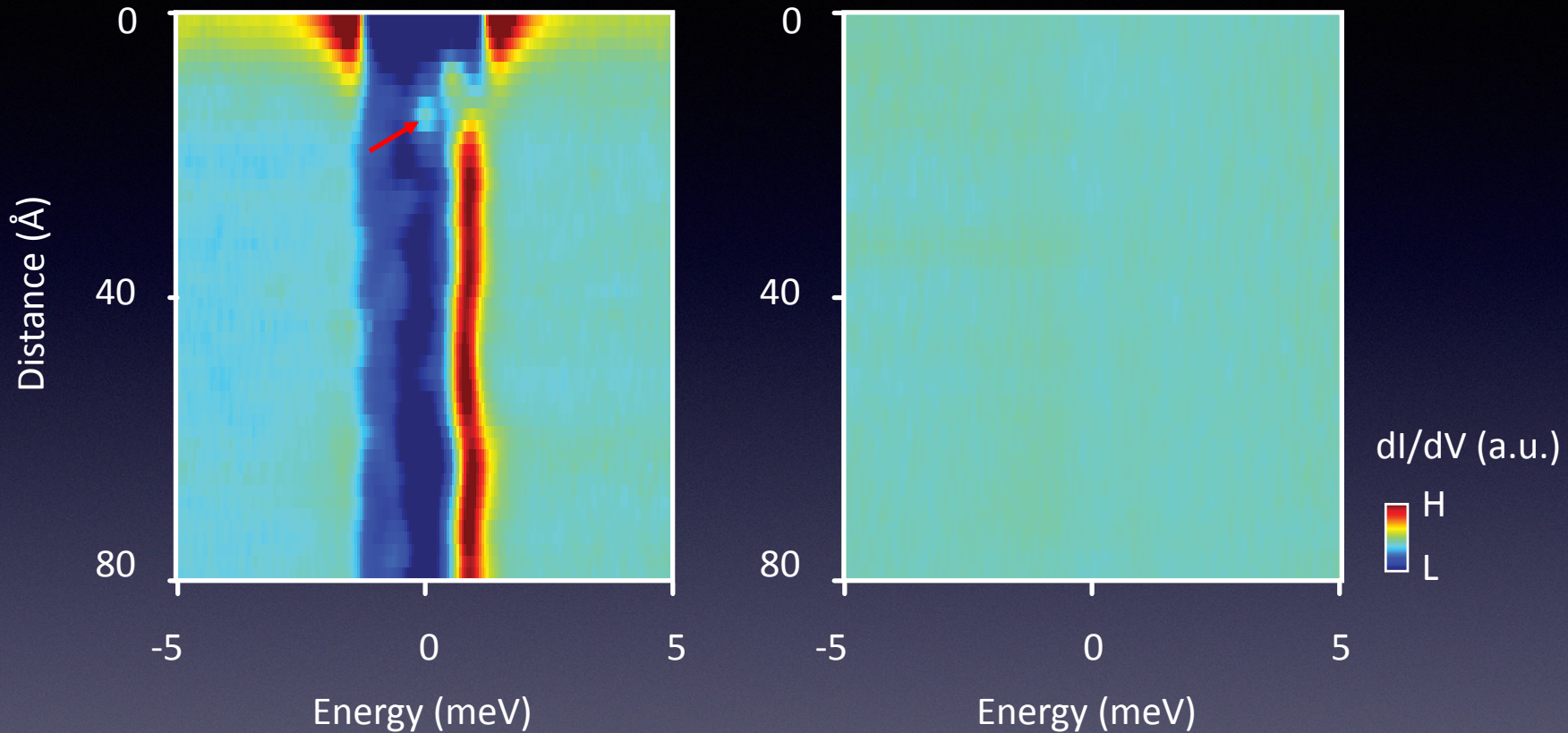
²Department of Physics, Yale University, New Haven, Connecticut 06520, USA

(Received 10 December 2014; published 9 March 2015)

Zero bias peak at the chains ends



Kondo effect? ZBP due to superconductivity?



Note: ZBP end state separate from the Shiba bands which also change at the edge

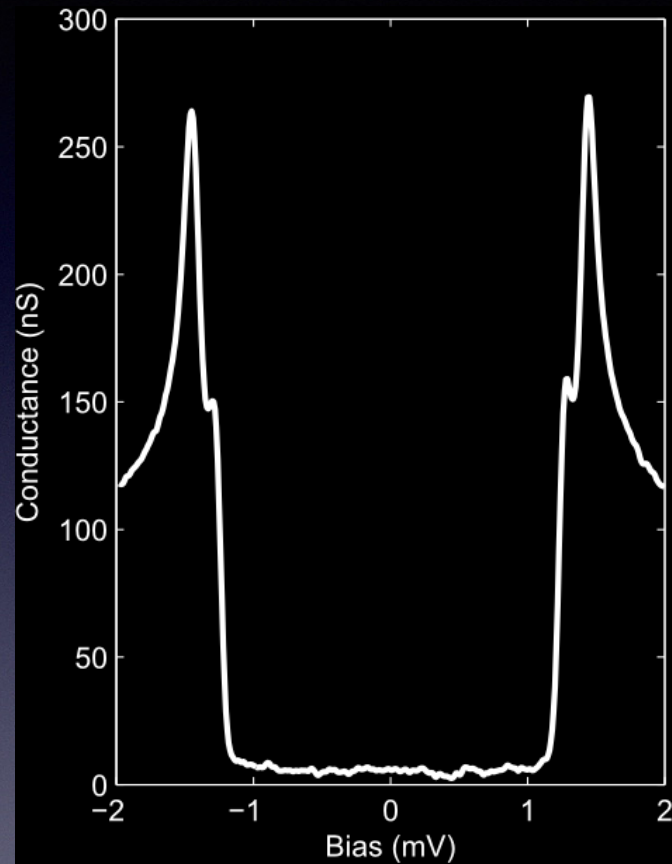
$B = 0$

$B = 100\text{mT} > B_c$

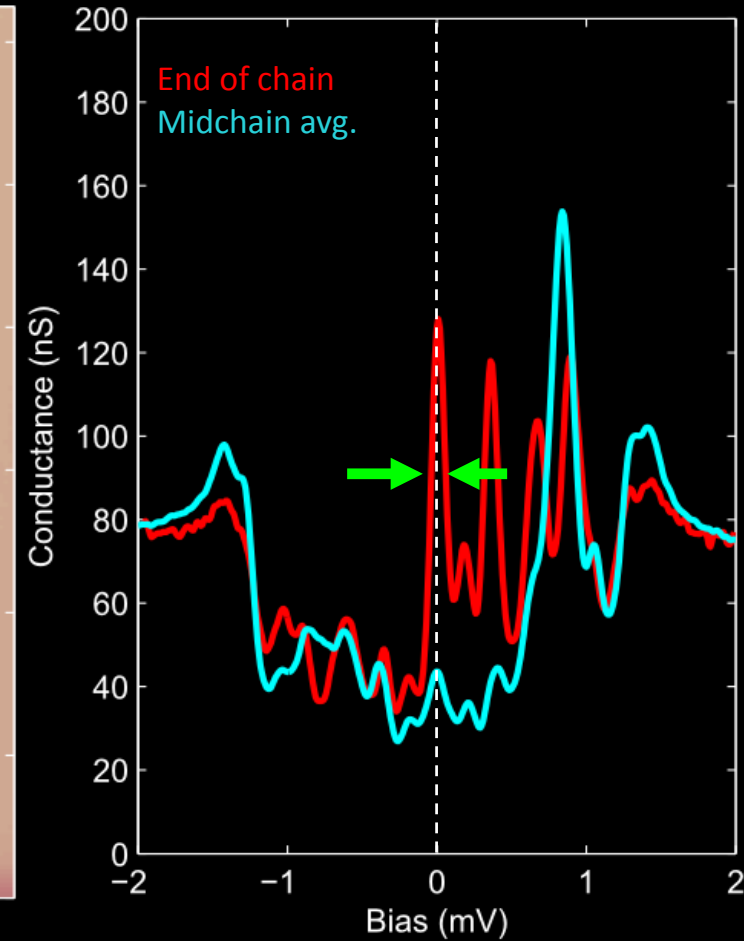
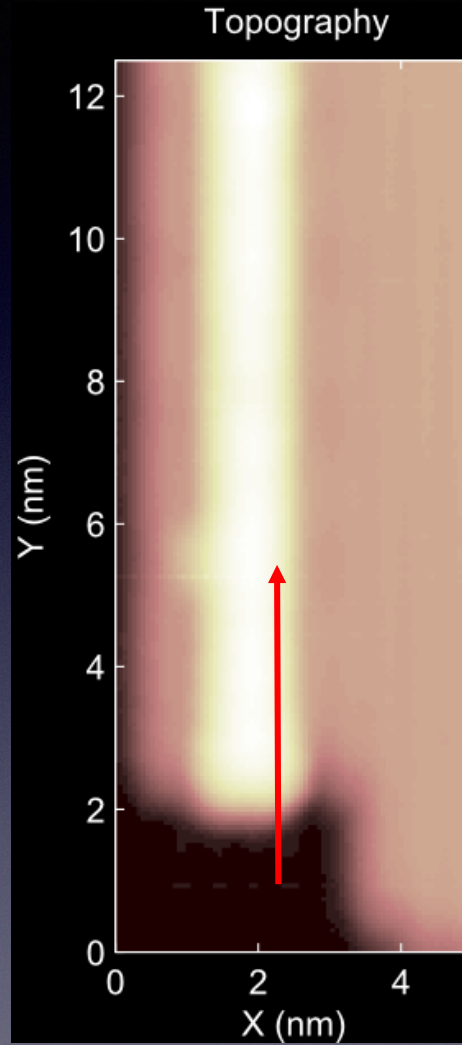
States are clearly related to superconductivity!

Current bound on ZERO with $90\mu\text{eV}$ resolution

Factor of 5 improvement from 1.4K



Pb at 20mK
 $T_{\text{electrons}}=250\text{mK}$
Predicted
two gaps in Pb



Splitting $< 45\mu\text{eV}$



Ben Feldman



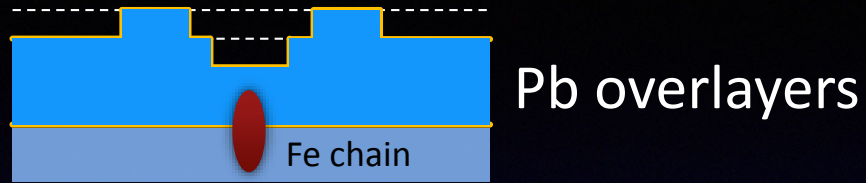
Ilya Drozdov



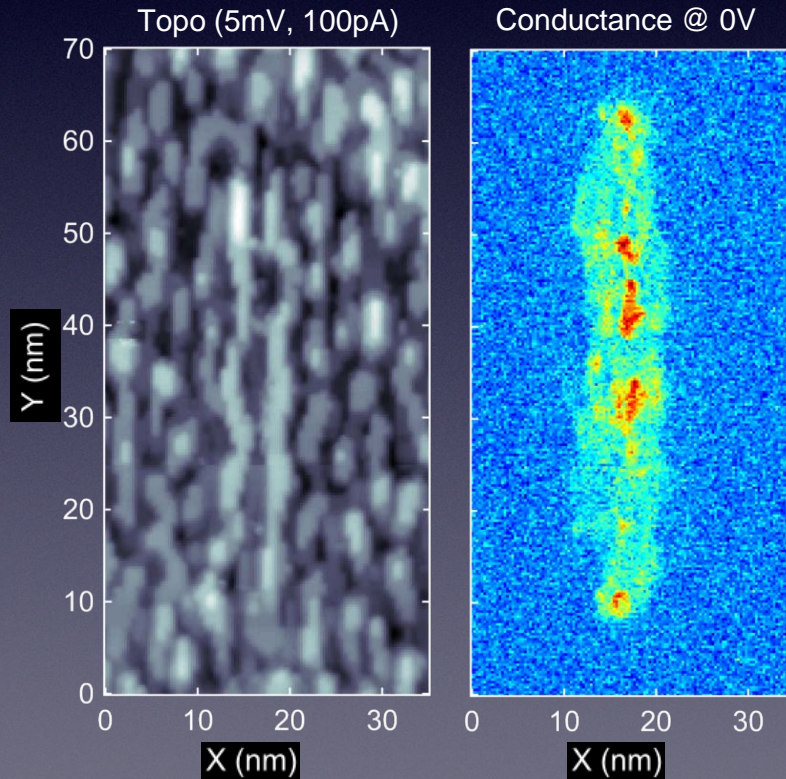
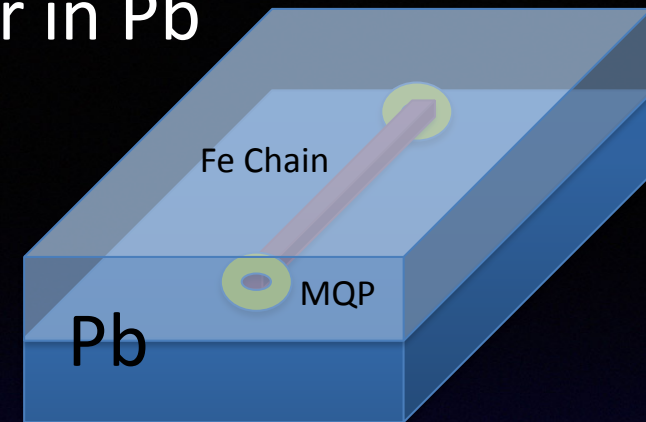
Mallika Randeria

Imbedding the Fe Chains further in Pb

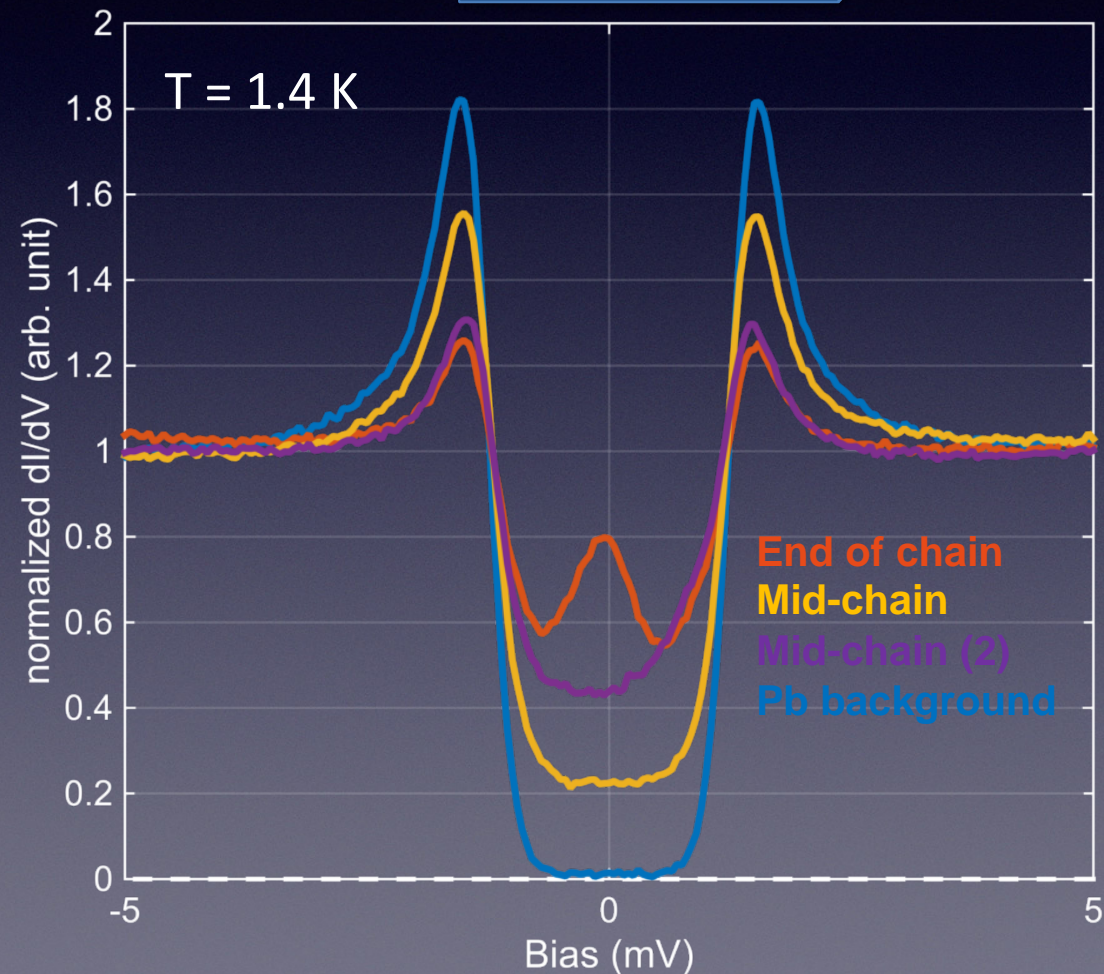
1.4K measurements



Pb Substrate



in-gap states



Sangjun Jeon



Yonglong Xie

Summary

Experimental progress:

- ✓ Magnetic chains on superconductor
- ✓ Spin polarized measurement:
 - (Modulated) Ferromagnetism
 - SOI present
- ✓ Observed end states at zero bias:
 - Reproducible on many wires
 - Related to Magnetism and Superconductivity
 - Consistent with FM + SOI scenario for Majorana fermions

THANK YOU!
QUESTIONS?

